HUDSON LABORATORIES of Columbia University

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TECHNICAL REPORT NO. 108

HYDROPHONE DEVELOPMENT AT HUDSON LABORATORIES

by Edward T. O'Neill

September 24, 1963

Hudson Laboratories
of
Columbia University
Dobbs Ferry, New York

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Director

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ABSTRACT

This report presents the salient points of hydrophone development at Hudson Laboratories in the past five years. Described herein are hydrophones designed for extreme ocean depths and others designed for the effective minimization of signal due to accelerative motion as opposed to the acoustic signal. Horizontal towable arrays as well as specially designed test equipment are also described.

CONTENTS

Figures

I INTRODUCTION

.   This writing supplements a report on hydrophones previously issued by this laboratory.[1] Developments in the hydrophone field made subsequent to the earlier report are presented. The need for a hydrophone for extremely high pressure use has had an associated developmental result. An instrument for rapid comparative evaluation of hydrophone sensitivity was devised during the experimental work on the high pressure hydrophone and this, too, is presented. A hydrophone was designed which effectively minimizes the signal output due to vertical accelerative motion. Using a variation of this same design, a towed hydrophone array was also constructed and has been very satisfactorily used for continuous seismic ocean profiling.[2] Since practically all of the hydrophones employ cylindrical piezoelectric elements, a consideration of the mechanical and peizoelectric characteristics of these elements is presented. In an "Associated Developments" section such things as special test units, a hydrophone for shot reception on a moving ship (mounted in a fuel tank), and a hydrophone encompassing an impedance converting transformer are considered. The first hydrophone to be presented is the successor to the "Standard Three-Element Hydrophone."[3] This hydrophone is one employing lead zirconate titanate material, produced by Clevite Electronic Components Corporation under the trade designation of PZT-5.

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[1] Edward T. O'Neill, Hydrophone development at Hudson Laboratories 1951 to 1958 (Hudson Laboratories of Columbia University Technical Report No. 70) February 15, 1959.

[2] C. S. Clay and W. L. Liang, "Continuous seismic profiling with matched filter detector." Hudson Laboratories of Columbia University Contribution No. 153, Geophysics 27, 786-795 (1962).

[3] Reviewed in report mentioned in footnote 1.

II GENERAL PURPOSE HYDROPHONE

This hydrophone design has been used for all of the ordinary research operations at the laboratory. Its active element consists of two piezoelectric cylinders (2.25" long × 1.5" o.d. × .125" wall thickness) of opposite polarity.

A. Assembly

The two oppositely polarized cylinders were series wired in the manner shown in Fig. 1. Since the outer electrodes of the two cylinders are wired together, this hydrophone design offers some advantage of diminishing electrostatic pickup by its shielding effect.

An epoxy dowel was used for a twofold purpose:

1. To facilitate the wiring and assembly operation.

2. To diminish the high exotherm in the curing of the rather large concentrated mass of epoxy plastic in subsequent assembly operation.

The wired crystals and dowel were lowered into the neoprene boot which was selected for its similarity to rho C rubber, approximating the acoustic properties of sea water. The neoprene boot was then filled with a room temperature curing epoxy resin. To lower the viscosity of the plastic material, making it more suitable for the liberation of entrapped air, about 8 percent styrene oxide was added to the plastic during the mixing operation. The plastic-filled hydrophone was allowed to cure for about 12 hrs before calibration.

EPOXY RESIN

POSITIVE POLARITY

NEOPRENE BOOT

NEGATIVE POLARITY

LEAD ZIRCONATE TITANATE CYLINDERS (REVERSED POLARITY)

EPOXY DOWEL
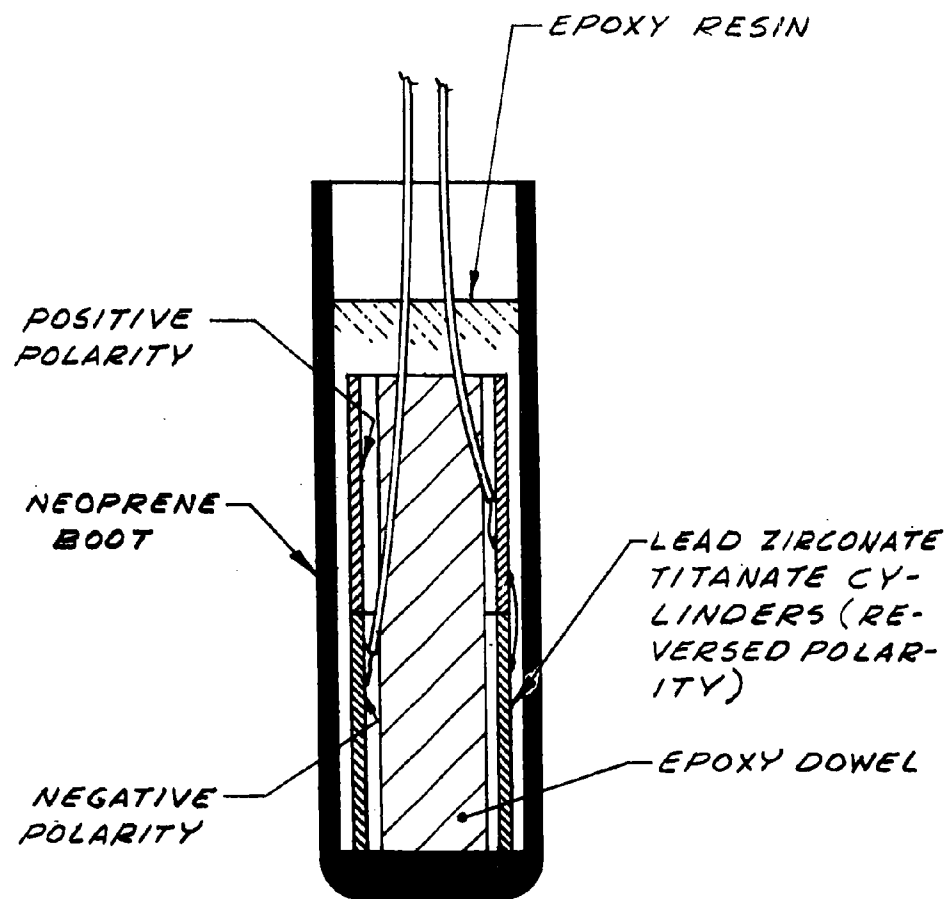
GENERAL PURPOSE ZIRCONATE TITANATE HYDROPHONE

Figure 1

B. Characteristics of Hydrophone

    1. Sensitivity[4] – This hydrophone which was series wired had a sensitivity of -87 db/dyne cm^2 – reference 1 volt.[5]

    2. Capacity – Capacity of the assembled unit was .012 mfd.

    3. Advantages over earlier barium titanate hydrophones – The chief advantages of this hydrophone over the barium titanate variety were due to the inherent properties of the piezoelectric material (lead zirconate titanate).

        a. This material has a higher dielectric constant than barium titanate[6] which accounts for a higher electrical capacitance desirable in low frequency acoustic listening.

        b. Because of the higher piezoelectric activity of the newer material, this hydrophone with two cylinders was twice as sensitive as the earlier three-element barium titanate variety.

        c. This hydrophone had a wider range of temperature in which it could be used while still retaining a uniform signal response. The upper and lower curie points of this newer material were well outside the normal temperature range in which the hydrophones were to be used. In the case of even modified barium titanate material the lower curie point was very close to the ambient sea water temperature.

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[4] See Low Frequency Calibration Curve – Fig. 2, and typical calibration and directionality patterns for this hydrophone in Appendix D.

[5] Henceforth all db measurements in this report will have this same reference.

[6] See Appendix A, "Comparison of Piezoelectric Materials."
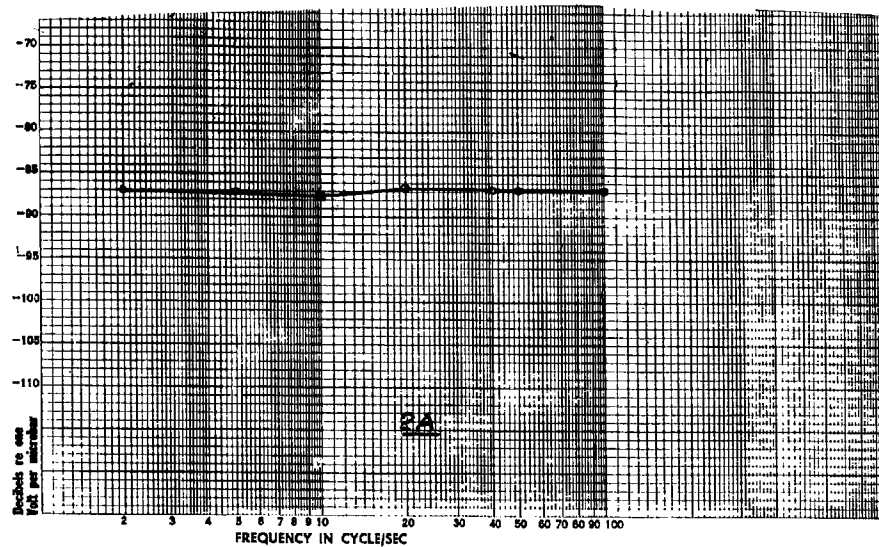
ATMOSPHERIC CALIBRATION
(EPOXY FILLED HYDROPHONE)
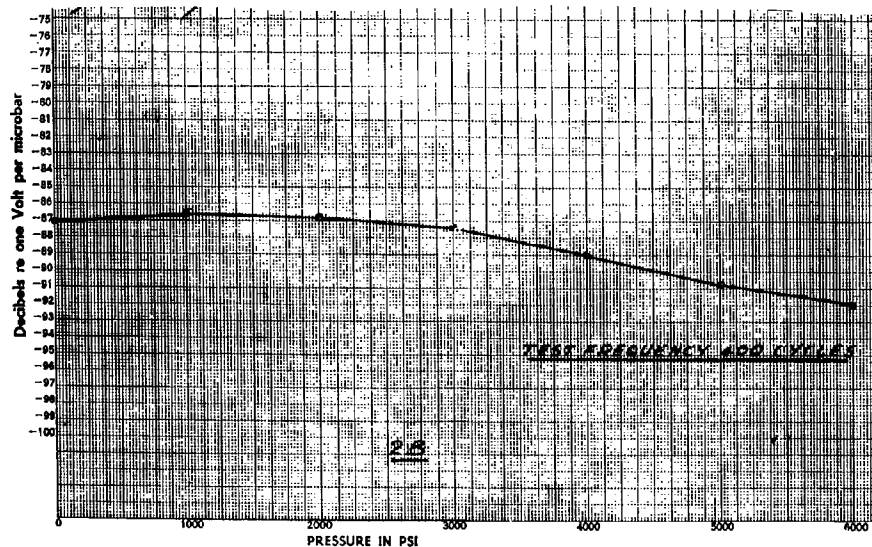
HIGH PRESSURE CALIBRATION
(EPOXY FILLED HYDROPHONE)

Figure 2A & B

III HIGH PRESSURE HYDROPHONE

A. Background

Our standard plastic-filled hydrophones have been used satisfactorily to varying depths of ocean, in some cases sustaining pressures up to 2000 lbs. However, under pressures above 1000 lbs, a loss of sensitivity of from 1 to 2 db was observed.[7] Some failures had been noticed in laboratory pressure-tested units, especially where pressure on the hydrophone was relieved too rapidly, causing tensile failure in the crystals. The need for a foolproof hydrophone for unlimited ocean depth service led to the development of the hydrostatically balanced unit shown in Fig. 3. This pressure-compensated unit has performed satisfactorily at pressures up to 10,000 psi. The most effective use of the cylinder in hydrophone construction is in the air-filled, end-capped state. Under pressure, however, there is a sharp limitation in this type of design because of the inherent character of the piezoelectric material available. The design used here consisted of oil filling the end-capped cylinders and providing a capillary tube passage from this oil chamber to an external oil reservoir. This design functions on the principle of the Helmholtz resonator whereby the resonance of the capillary is designed to be below the field of acoustic interest. Above the resonant frequency of the capillary design, the acoustic pressure does not transmit to the inside of the cylinder and therefore the inherent sensitivity of the hydrophone is preserved.

B. Description of High Pressure Hydrophone

This hydrophone employs cylindrical piezoelectrics for the active

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[7] Refer to Calibration Curve in Fig. 2.

POLYETHYLENE WIRE

SEAL GLANDS

AERO SEAL

STUD

OIL

ADAPTER

EPOXY RESIN

PZT5 - CYLINDER 1.5" O.D. X 2.25" LG. .125" WALL

NEOPRENE BOOT

CAPILLARY

RELIEF VALVE

SPRING

O-RING

SOLDER

OIL

$9\frac{7}{8}"$

$1\frac{3}{4}"$ DIA.
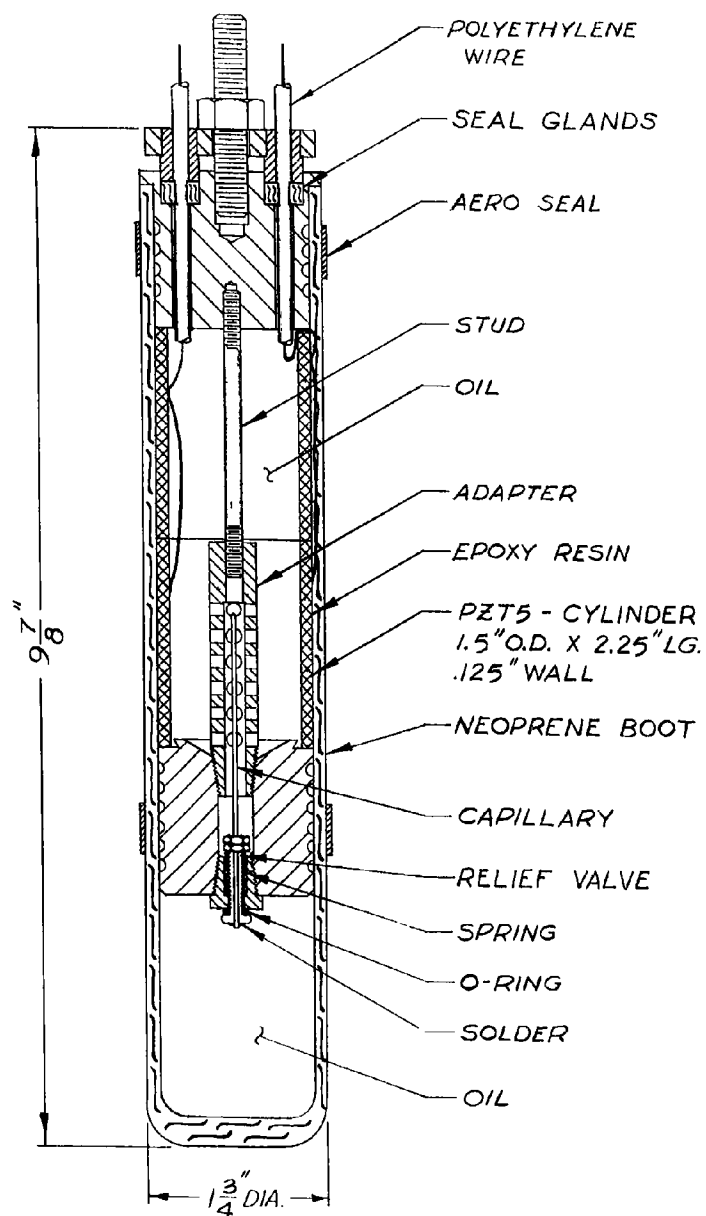
PRESSURE-BALANCED HIGH PRESSURE HYDROPHONE
CAPILLARY TYPE

Figure 3

element. Although beneficial from the standpoint of affording high sensitivity due to the mechanical stress enhancement of the cylinder, the cylindrical shape will subject the material to high compressive stress when using air-filled or plastic-filled assembly methods. Through the use of a pressure-balancing technique the pressure within the cylinder was maintained equal to the ambient sea pressure, thereby eliminating excessive stresses which could otherwise mechanically damage the cylinder or cause depolarization. The sensitivity of the oil-filled hydrophone was preserved by the use of a capillary tube which offered sufficient impedance to the acoustic pressure wave, yet at the same time permitted pressure equalization as the unit was subjected to high hydrostatic pressure. The capillary tube was necessarily dimensioned to be compatible with the viscosity of the high dielectric oil used. The hydrophone was jacketed with a neoprene "boot" having properties closely approximating rho C rubber with density and sound velocity close to the same properties in sea water. The boot' also provided a reservoir of oil to compensate for the compression of the oil within the cylinder when the hydrophone was subjected to extreme hydrostatic pressure. (For the oil used, the compressibility at 3000 psi is about 2.5%.)

C. Developmental Problems Encountered

1. Capillary

By empirical means a 3-in. length of capillary tube .020" I.D. was finally used. The capillary size and length were necessarily a function of the viscosity, compressibility, and volume of the oil used.

2. Selection of Oil

The oil used in the pressure-balancing operation had to be of a high dielectric quality and reasonably uniform in its viscosity over the operable temperature and pressure range. The oil finally selected for the purpose was Dow Corning silicone oil No. 200 with a viscosity of 350 centistokes (volume resistivity 6×10^4 ohms/cm).

3. Pressure Relief Valve

Since tensile strength of the ceramic material is low, any sudden relief of external pressure on such a pressure-compensated hydrophone might have permitted a build up of an excessive internal pressure and a consequent damage to the crystal. To prevent this, a relief valve was incorporated into the capillary hardware and was adjusted for a release setting of 15 psi. In subsequent units, commercially available lubrication fittings were used for this purpose.[8]

4. Feed-Through Seals

The high pressure hydrophones used more numerously were provided with a solid conductor polyethylene insulated wire which was used in conjunction with a pressure gland type of seal. In the case of some hydrophone assemblies, where the units were fitted on to a preamp container, a high pressure feed-through fitting made by the Mecca Corporation was employed.[9]

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[8] See Appendix B "Source of Material."

[9] Ibid.

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D. Assembly Procedure

    1. Crystal Preparation

The cylindrical crystals were thoroughly cleaned with trichloro-
ethylene and oven dried. (Since the crystals are polarized in an
oil bath during manufacture, cleaning at this stage must be thorough
if proper plastic adhesion is to be obtained in the subsequent ce-
menting operation.) The crystals were then wired with a thin
insulated connecting wire leaving pigtails of about 2 in. for con-
nection to the feed-through wires and the cylinders were cemented
together axially in the manner discussed in Section D-3.

    2. Preparation of Metal Parts

After thorough cleaning with trichloroethylene the metal parts
were etched with a solution such as:

        27% concentrated H_2SO_4

        3% sodium dichromate

        70% distilled water.

(Etching should take place for about 10 min at 150°F.) The end
seal piece was then assembled and the crystal connecting wires
soldered to the feed-through leads.

    3. Cementing Operation

In addition to the cementing material (a room-temperature curing
epoxy plastic) a metal reinforcing rod was utilized to give the unit
additional mechanical rigidity. The prepared plastic was applied
to the etched metallic surfaces and to the crystal ends. The pieces
were then assembled as shown in Fig. 3 and the threaded rod made

-10-

tight by the use of a torque wrench applying a force of 5 ft-lbs.

4. Oil Filling Operation

At least 12 hrs after the cementing operation, the unit was oil filled. The relief valve and capillary were installed using extreme care to remove all traces of air from within the unit by employing a vacuum chamber for the de-aeration operation.

5. Applying Neoprene Jacket

A measured quantity of oil was placed in the bottom of the precut hydrophone boot. The boot was then slid up over the assembly subsequent to operation D-4. When the boot was properly located, a hose clamp was applied securing it to the corrugated metal hardware.

6. Testing Final Assembly

Previous to the final calibration of the unit, a preliminary test of capacity was made to assure proper wiring. A resistance check should be made severally between the leads and the exposed metal parts. These should have resistance measurements of 100 megohms or higher.

7. Sensitivity[10] - Capacity

The parallel-wired hydrophone described had a sensitivity of -92 db and a capacity of .046 mfd. For the high pressure test, the hydrophone was calibrated at 400 cycles up to a pressure of 6000 psi and exhibited a uniform sensitivity under pressure.

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[10] See Calibration Curves - Fig. 4.
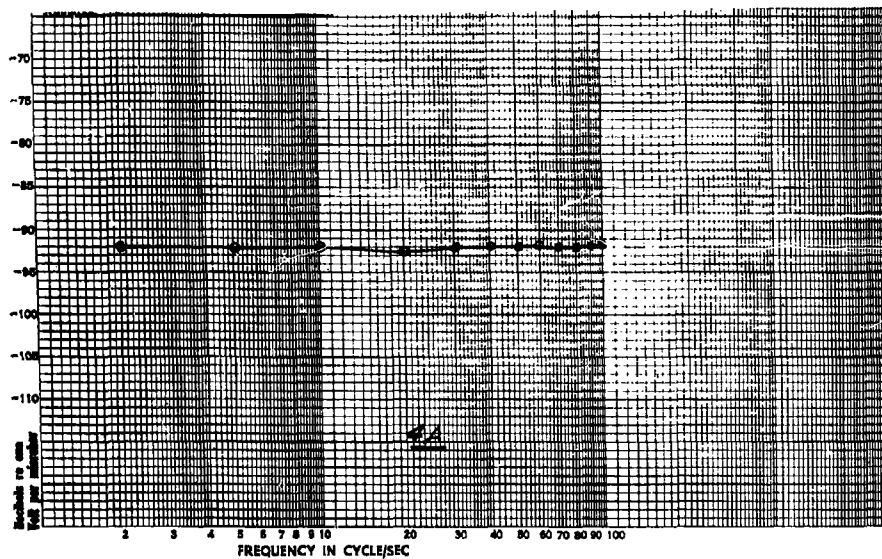
ATMOSPHERIC CALIBRATION
(HIGH PRESSURE HYDROPHONE)
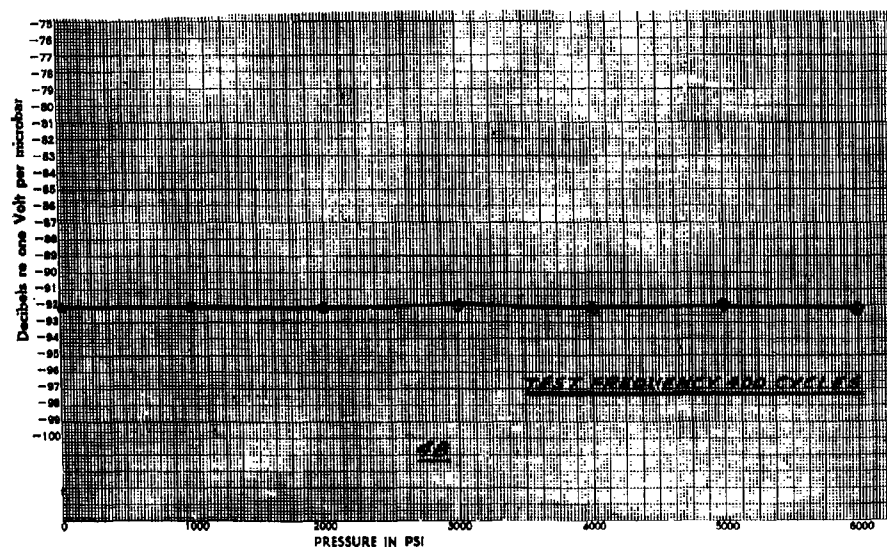
HIGH PRESSURE CALIBRATION
(HIGH PRESSURE HYDROPHONE)

Figure 4A & B

E. Advantages of Pressure-Balanced Hydrophones

    1. Aside from the ability of this unit to function at almost unlimited
ocean depths, it has another advantage relating to the inherent
nature of the piezoelectric material used.[11] Under normal con-
struction, particularly with cylindrical shapes, excessive stress
can depolarize these piezoelectric materials; however, this is
not so in the case of liquid-filled pressure-balanced units.

    2. For specific purposes, the hydrophone using a capillary feature
can be designed mechanically to reject undesirable low frequency
noise which might otherwise cause preamplifier overloading. The
desired low frequency cutoff effect can be accomplished by using
the following equation:

$$f_o = \frac{D^4 \times B_e}{256 \, u l V_e}$$

where

        D = diameter of capillary (in.)

        l = length of capillary (in.)

        B_e = bulk modulus of oil (psi) Dow Corning No. 200
at 23° C and 3000 psi is 1.44×10^5 (psi)

        V_e = volume of liquid within cylinder (in³)

        u = dynamic viscosity of the oil (lb-sec/in²) .

    3. Durability

The capillary type high pressure hydrophone was successfully
tested in the proximity of explosive charges in deep and shallow

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[11] H. H. A. Kreuger and Don Berlincourt, Effects of High Static Stress on the
Piezoelectric Properties of Transducer Materials, Electronic Research Division,
Clevite Corp. Engrg. Memo No. 61-12,(May 1961) p. 50.

water. The hydrophones were suspended on a frame within 5 ft of a 5-lb tetryl charge. No mechanical damage or impairment of performance was caused by repeated explosive testing.

F. Limitation of Capillary Type High Pressure Hydrophone

The capillary type pressure-balanced hydrophone for high pressure use had some undue hysteresis subsequent to pressurization. After return to atmospheric pressure, some delay was noticed for the hydrophone to stabilize and return to the original atmospheric calibration. To meet this problem, an alternate design of pressure-balanced hydrophone,(Fig. 5), using dually opposed relief valves, was investigated and proved to be an improvement over the capillary unit with respect to sensitivity recovery time.

IV ACCELERATION-BALANCED HYDROPHONES

A. Principle Involved

A piezoelectric cylinder will generate electrical energy as a consequence of any motion which exerts a stress on the crystal. Hydrophones are commonly supported on cables by means of which they are lowered into the water. Any vertical motion of such a cable suspension will impart some stress on the piezoelectric material and consequently will generate a voltage which might be termed "noise" as distinguished from ambient or discrete listening.

Figure 6 graphically shows how piezoelectric cylinders might be placed on either side of a platform secured to a cable having accelerative motion in the vertical direction. As the cable moves in an upward direction, crystal "A" will be compressed and will generate a voltage of certain polarity. Crystal "B"

-14-

SINGLE CONDUCTOR
INSULATED WIRE

SEAL GLANDS

AERO-SEAL

OIL

PZT5-CYLINDER
1.5"O.D. X 2.25"LG.
.125" WALL

EPOXY RESIN

NEOPRENE BOOT

DUALLY OPPOSED
RELIEF VALVES

OIL RESERVOIR
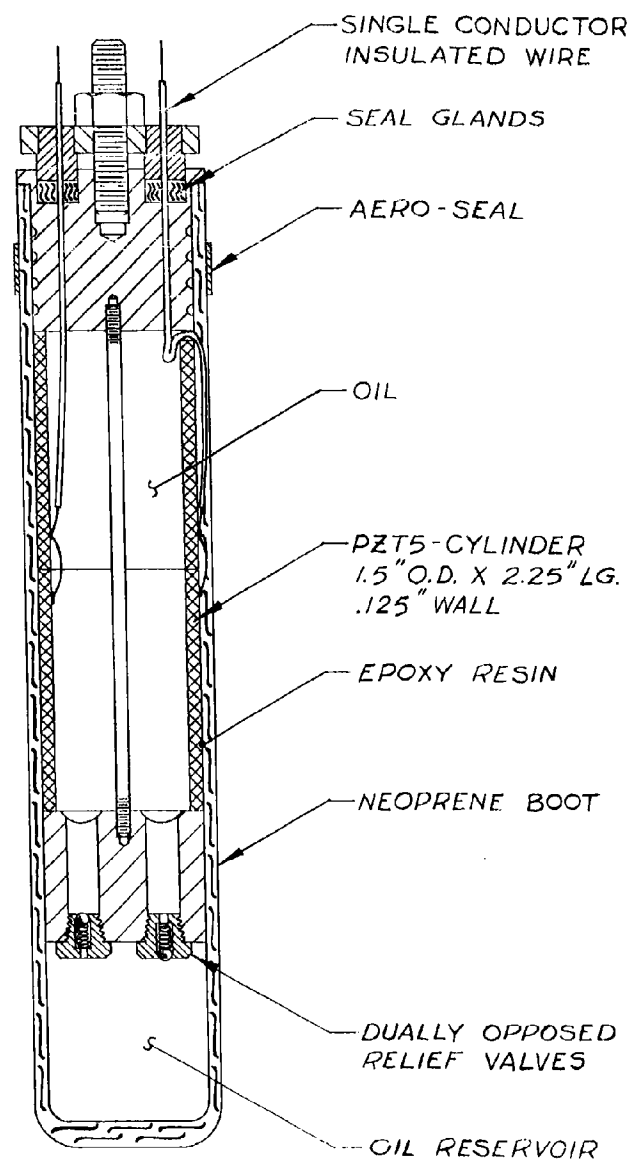
PRESSURE-BALANCED HIGH PRESSURE HYDROPHONE
RELIEF VALVE TYPE

Figure 5

-15-
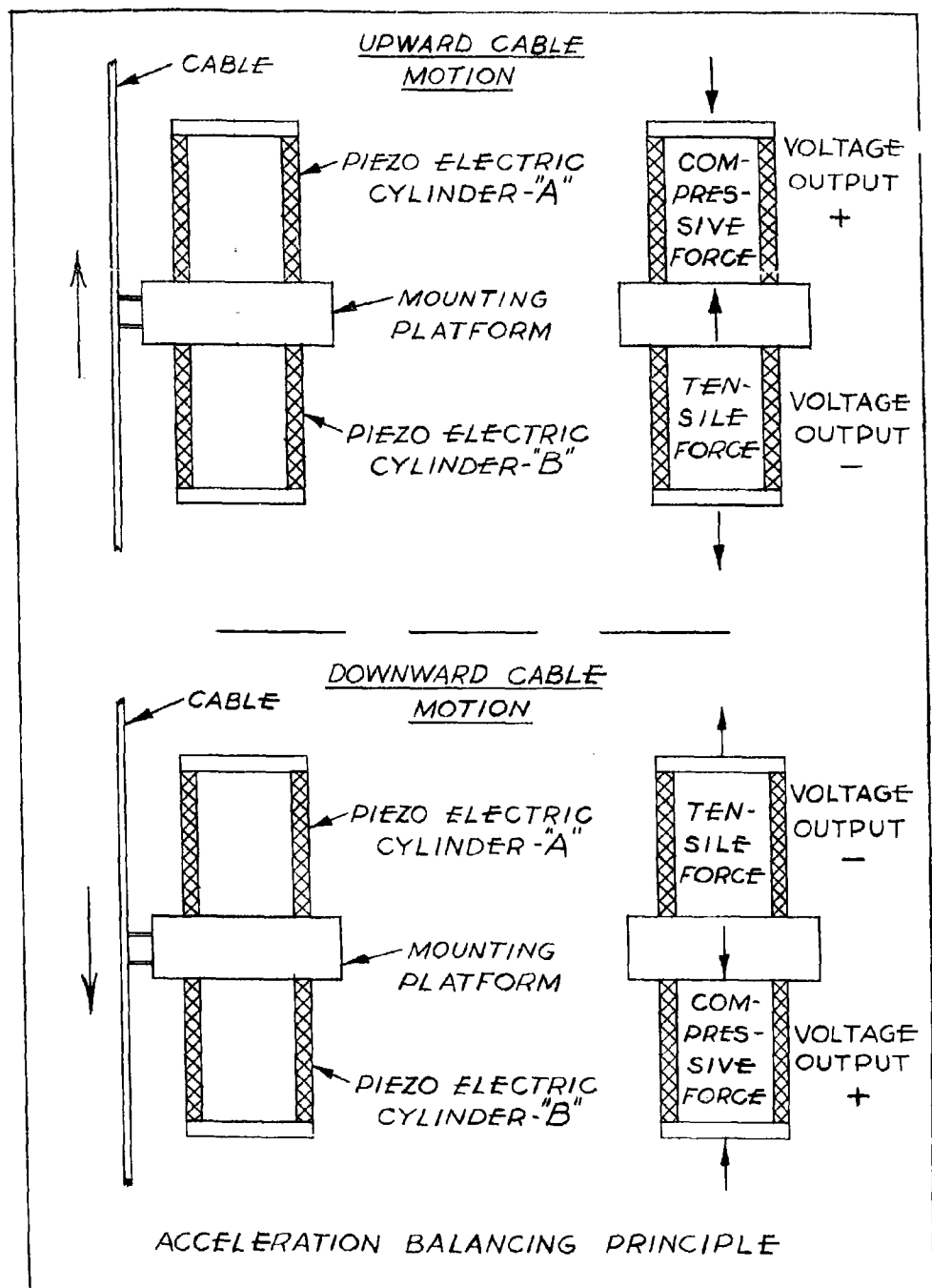
Figure 6

is at this time subjected to a vertical tensile force producing a voltage of equal and opposite polarity canceling the electrical influence of the upward cable motion. As the cable moves downward, the polarity of the voltage output of each crystal is reversed and again their combined output voltage is minimal.

A vibration table was used[12] for the experimental work on the acceleration-balanced types of hydrophones. The experimental results showed a marked reduction of signal due to vertical accelerative motion. As much as 30 db of undesirable signal was rejected by this balancing method.

B. Low Pressure Acceleration-Balanced Hydrophone

This standard acceleration-balanced hydrophone was an air-filled type of unit intended particularly for shallow water use (up to 1500 psi), (Fig. 7).

The unit consisted of two end-capped piezoelectric cylinders mounted on a common supporting plate, which was in turn the mount securing the completed unit to a cable or a shock mount.

1. Assembly Procedure

   a. The feed-through connectors were affixed to the supporting plate, leaving a sufficient length of wire pigtail for the subsequent wiring operation.

   b. The cylindrical piezoelectric elements were cemented to the supporting plate using the same epoxy mixture referred to earlier in this report. The wires fastened to the external electrodes of the crystals were fed through a slot which was ground in the crystal edge. In this cementing operation the

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[12] See Section on Associated Developments – Vibration Table, p. 44.

-17-

END PIECE

PZT5-CYLINDER
1.5"O.D. X 2.25"LG.
.125" WALL

NEOPRENE
SLEEVE

CLAMPING
WIRE

CONNECTOR
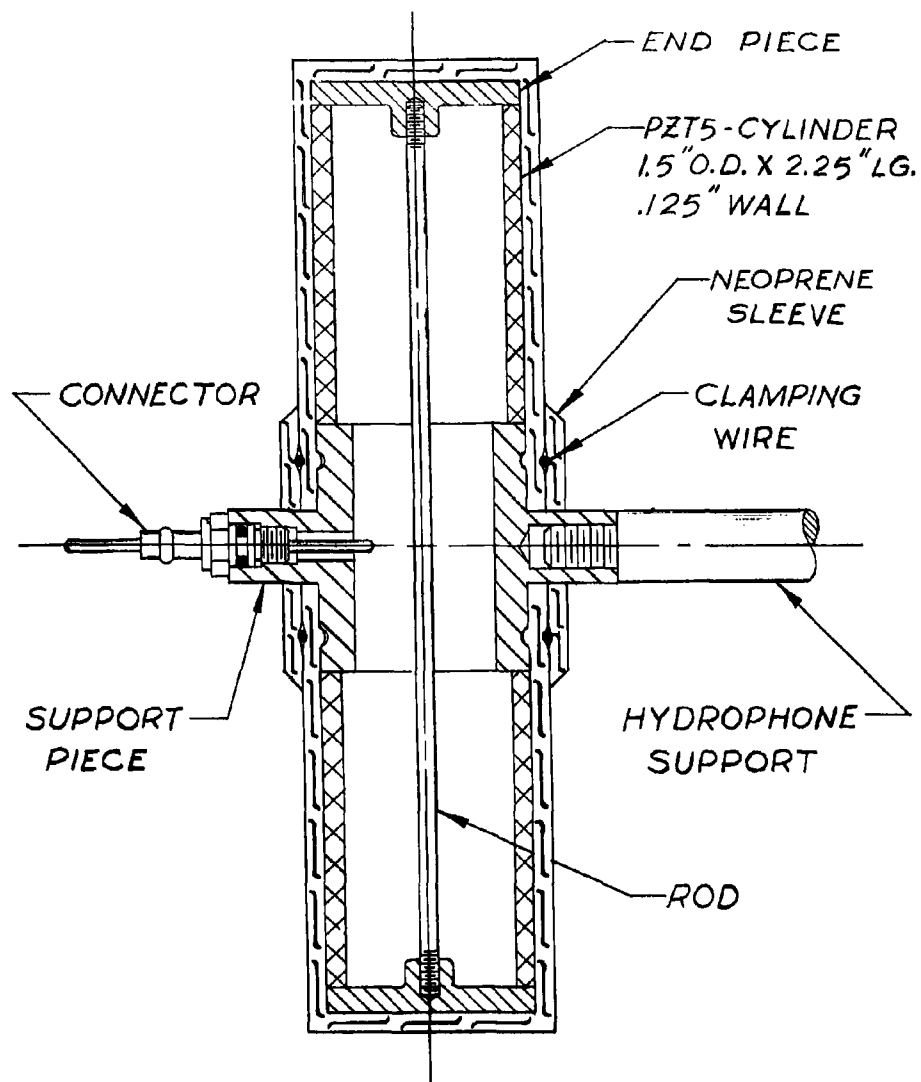
SUPPORT
PIECE

HYDROPHONE
SUPPORT

ROD

Figure 7

LOW PRESSURE
ACCELERATION BALANCED HYDROPHONE

slot was completely filled with plastic to prevent intrusion of the neoprene jacket into the cylinder when exposed to high hydrostatic pressure.

c. Connected by a threaded rod the end plates were assembled and further secured by using epoxy cement.

d. Neoprene jackets were applied over each single crystal and secured by means of a clamping wire after which a neoprene sleeve was applied as an additional protection against corrosion.

2. Sensitivity - Capacity

This unit, using lead zirconate titanate piezoelectric cylinders in a series-wired configuration gave a sensitivity of -87 db and a capacity of .012 mfd.

In a parallel-wired construction, the sensitivity was -92 db and capacity was .048 mfd.

C. High Pressure Acceleration-Balanced Unit

Utilizing the capillary and pressure relief valve technique employed in the high pressure hydrophone design, the acceleration-balanced hydrophone can be used for unlimited ocean depths. This design is shown in Fig. 8.

D. Acceleration-Balanced Hydrophone (Self-Contained Mounting)

By means of the method exhibited in Fig. 9, it is possible to support any conventional hydrophone, high or low pressure, at some critical point at which the voltage due to vertical accelerative motion will be infinitesimal.

1. Description of Mount

The frame mounting was made of threaded rod and an upper and lower support or stiffener. After the proper point of clamping

ALEMITE #1641B

ALEMITE #47640

END PIECE

CAPILLARY

CLAMPING WIRE

SUPPORT PIECE

CONNECTOR

NEOPRENE SLEEVE

ROD

NEOPRENE BOOT

CRYSTAL

END PIECE
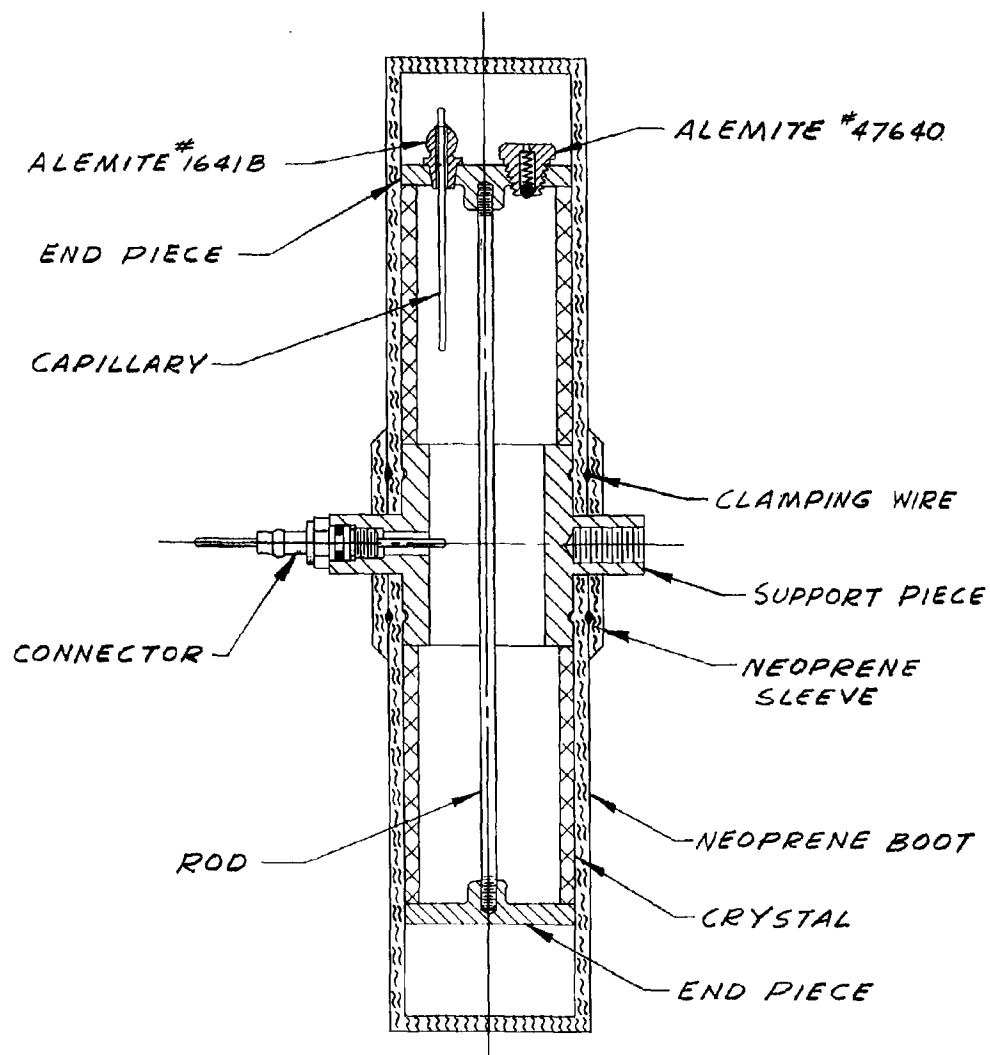
Figure 8

HIGH PRESSURE
ACCELERATION BALANCED HYDROPHONE

STIFFENER

ROD

CONNECTOR

NEOPRENE
SLEEVE

CLAMPING
WIRE

PZT5-CYLINDER
1.5" O.D.
2.25" LONG
.125" WALL

ADJUSTING
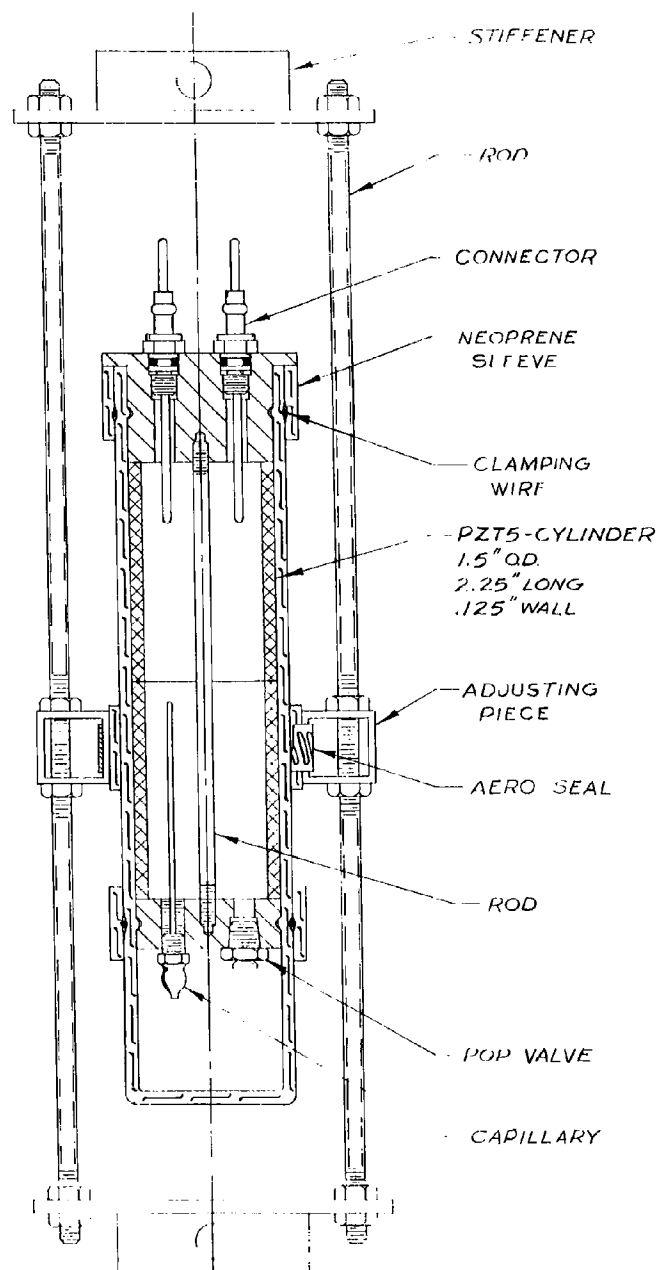PIECE

AERO SEAL

ROD

POP VALVE

CAPILLARY

Figure 9
MOUNTED HIGH PRESSURE
ACCELERATION BALANCED HYDROPHONE.

-21-

was determined according to the procedure outlined in the following paragraph the hydrophone was secured to the rods by means of a hose clamp.

2. Balancing Procedure

The hydrophone was temporarily secured in the mounting frame fastened to the armature of the shaker table. It was found practical to balance the hydrophone with the shaker table set to a frequency of 100 cycles at a force of about 1 g. The hydrophone was adjusted vertically in the mounting frame. The amount of voltage output from the hydrophone should be at a minimum when the clamp is finally secured. For practical purposes the greatest differential between a balanced and an unbalanced hydrophone has been noticeable in the frequencies below 100 cycles. (The mounted hydrophone must be used in the field in the same orientation that it was used in in the balancing operation.)

V TOWABLE HYDROPHONE ARRAY (FIG. 10)

A. Background

For a particular use in continuous seismic profile study, a parallel-wired multi-element hydrophone array was assembled for towing purposes. The individual hydrophones were spaced in their respective locations in a neoprene hose and the entire assembly was oil filled. Each of the hydrophone elements used in the towable array for shallow use employed the acceleration balancing principle (Fig. 11A). The supporting platform was made of lucite drilled to accommodate signal corps wire (WD-ITT) which was used as the
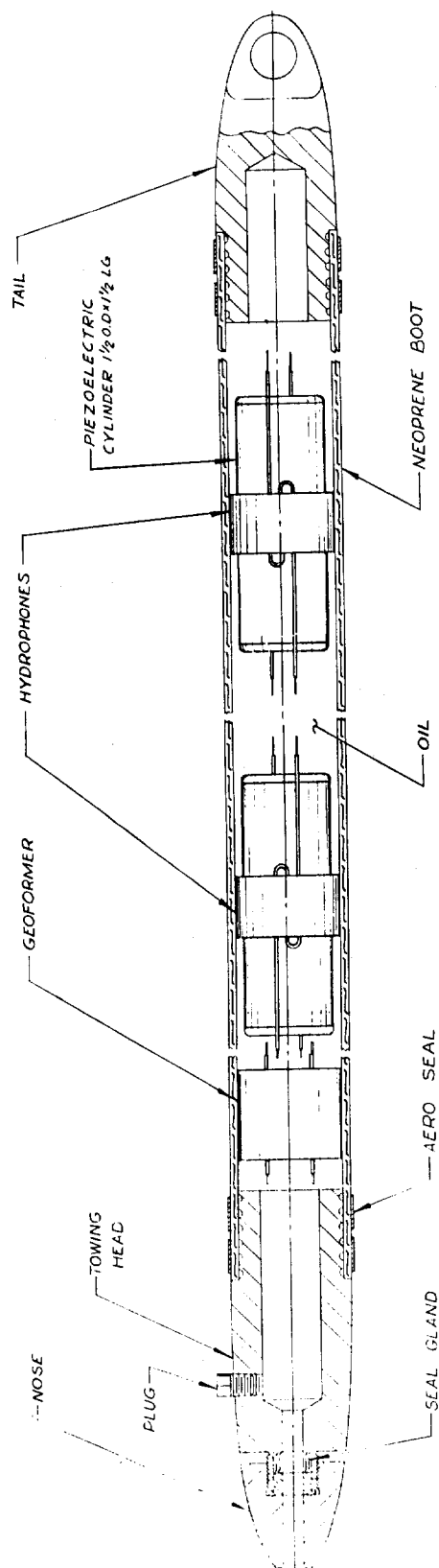
"TOWED SNAKE" ARRAY USING ACCELERATION BALANCED HYDROPHONES

Figure 10

END PIECE SUPPORTING MOUNT PZT5-CYLINDER 1.5"O.D. X 2.25"LONG. .125" WALL

ROD
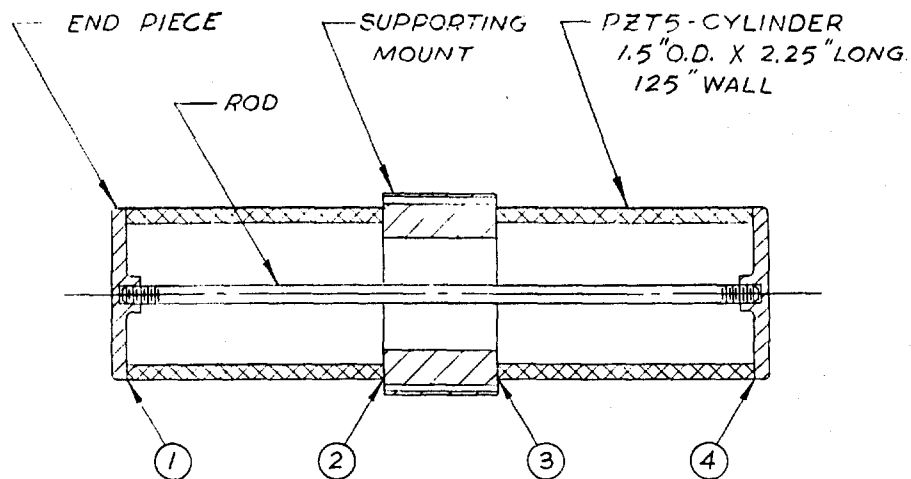
① ② ③ ④

NOTE: CEMENTED WITH ARALDITE
AT POINTS ①②③④

ACCELERATION BALANCED UNIT FOR SHALLOW "TOWED SNAKE" ARRAY

PZT5-CYLINDER 1.5"O.D. X 2.25 LG. .125" WALL SUPPORTING MOUNT PRESSURE RELIEF VALVE

① ② ③ ④

ROD

END PIECE-"A"

END PIECE-"B"

CAPILLARY
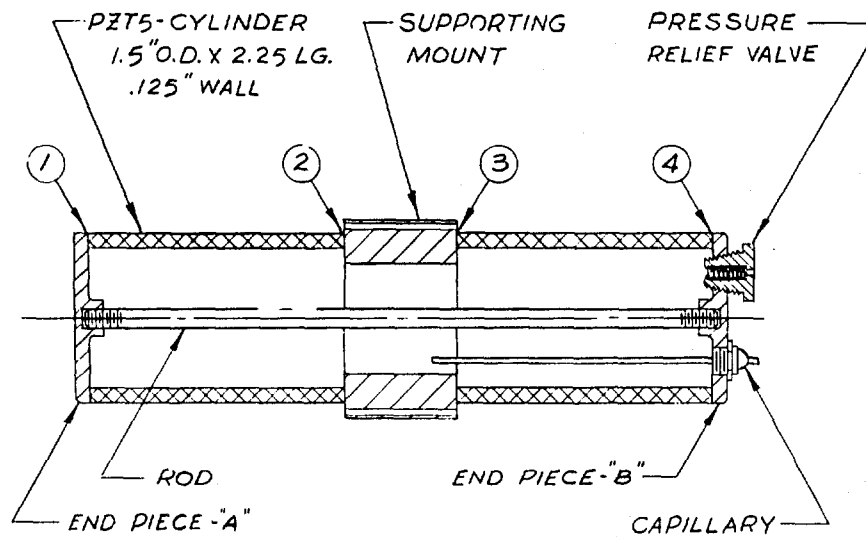
NOTE: CEMENTED WITH ARALDITE
AT POINTS ①②③④

ACCELERATION BALANCED UNIT FOR DEEP "TOWED SNAKE" ARRAY

Figure 11A & B

electrical conductor and, because of its tensile strength, was valuable in the assembly operation where the hydrophone was drawn into the outer neoprene covering. In the array for deep hydrostatic use, a design of individual pressure-balanced hydrophone elements such as shown in Fig. 11B was used.

Several varieties of hydrophone assemblies were tested in the development of the towed array. These are illustrated in Figs. 13 and 14. Although recent tests have shown considerable advantage in reduction of flow noise in the single-cylinder hydrophone design, the basic assembly techniques described are applicable to all varieties of individual array components.

At the present time only preliminary experimental work has been completed using laminated piezoelectric discs. Piezoelectric discs appear to be very favorable for the accomplishment of noise suppression through acceleration balancing but they are difficult to employ in a pressure balancing design for deep water use. This is due to the fact that in the shear mode of operation large mechanical excursions are encountered and the compliance of the oil backing must be considerable. The compliance is a function of the volume of the backing oil divided by the bulk modulus of the oil. Having secured the oil with the highest bulk modulus, the only variable parameter is the volume of the oil backing and this may prove to be impractical for compact hydrophone design.

B. Construction

The overall construction of the towed array included a sequence of operations: assembling elements, spacing elements in array, applying neoprene tubing, etc. Specific details of many of these operations duplicate some of the operations discussed in relation to earlier assembly procedures in this report and are, therefore, treated briefly.

-25-

NYLON TAIL

TOWED ARRAY

FLOAT

SOUND SOURCE
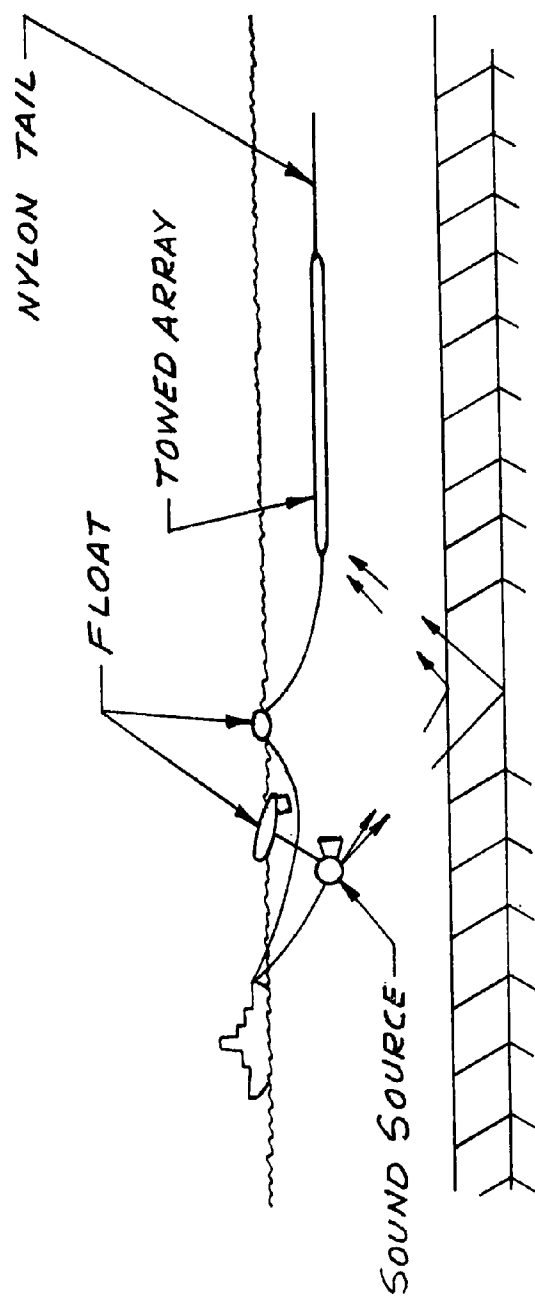
CONTINUOUS SEISMIC PROFILING SYSTEM

Figure 12

-26-

NEOPRENE TUBE

LUCITE

RG8U WIRE

CRYSTAL (PIEZOELECTRIC)

OIL

EPOXY PLASTIC
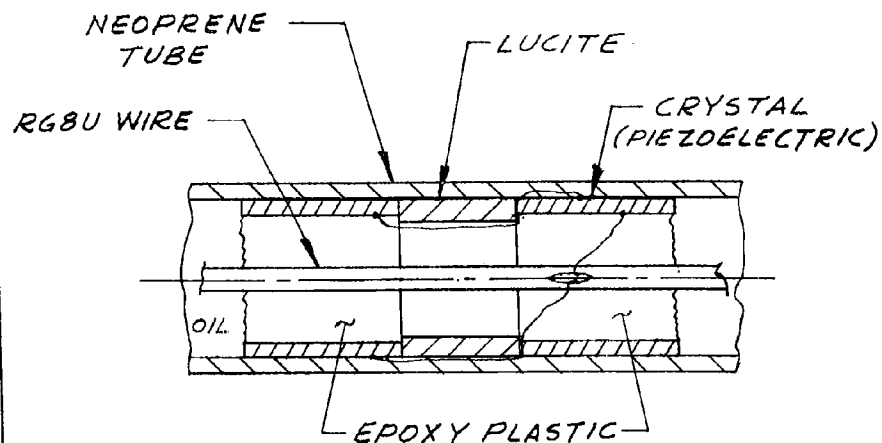
ACCELERATION BALANCED MTG
ON CO-AXIAL WIRE
(FOR SHALLOW WATER USE)

Figure 13A

NEOPRENE TUBE

PZT5 BILAMINATES

LUCITE

WDITT
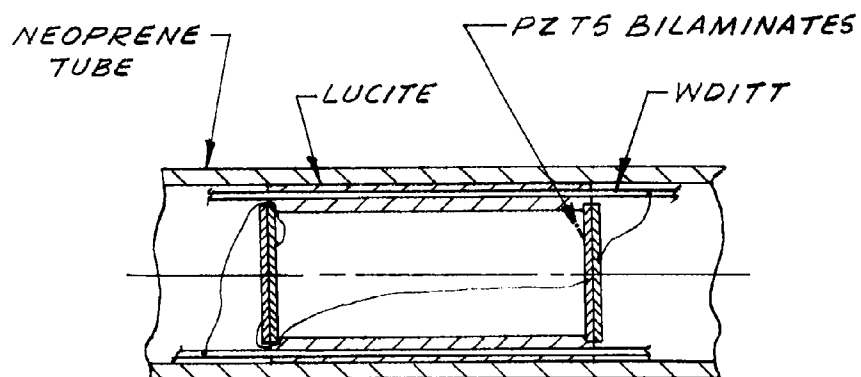
ACCELERATION BALANCED HYDROPHONE
FOR TOWED ARRAY
(USING PIEZOELECTRIC DISCS)

Figure 13B

NEOPRENE
TUBE

MOLDED POLYURETHENE

LUCITE

OIL   AIR

WDITT

ELECTRICAL
FEED-THRU

CRYSTAL (PIEZOELECTRIC)
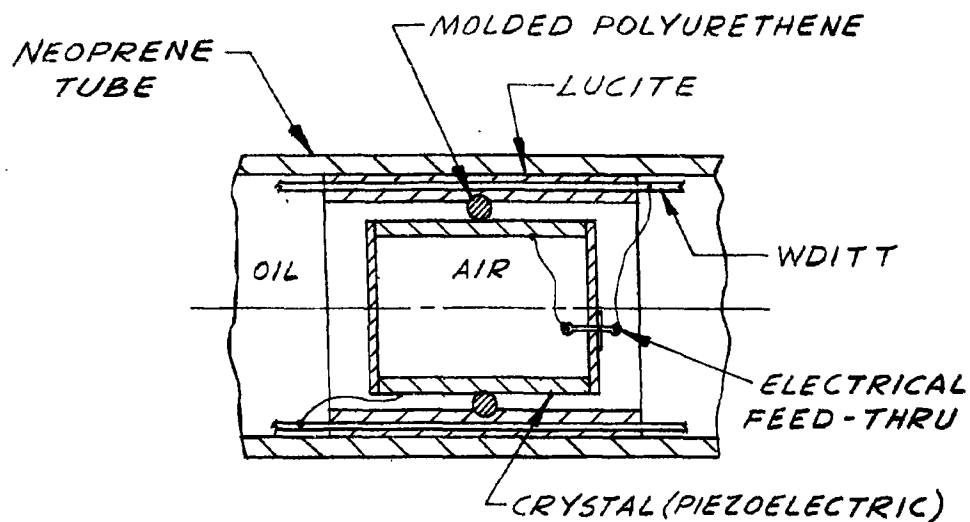
ACCELERATION BALANCED SINGLE CYLINDER
(FOR SHALLOW WATER USE)

Figure 14A

PRESSURE
RELIEF VALVE

CAPILLARY
TUBING

OIL

NEOPRENE
TUBE

OIL

CRYSTAL (PIEZOELECTRIC)
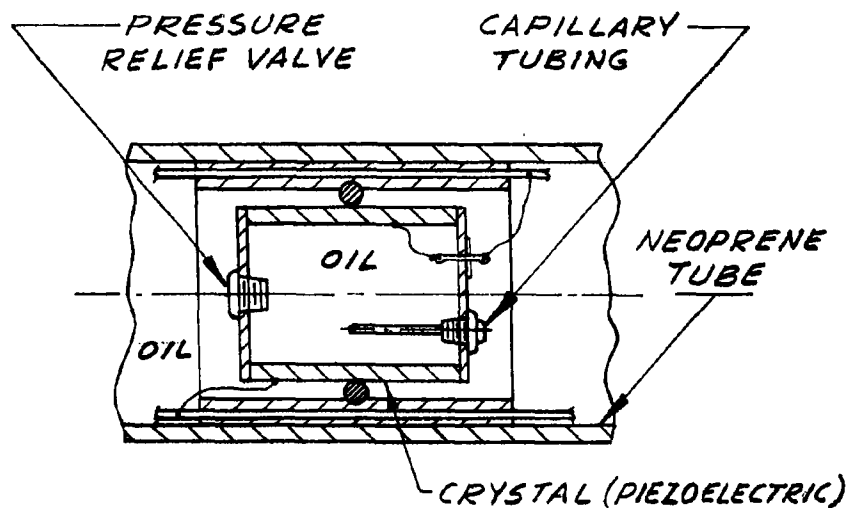
ACCELERATION BALANCED SINGLE CYLINDER
(FOR DEEP WATER USE)

Figure 14B

1. Individual Hydrophone Assembly Procedure

   The two crystals were cemented to either side of the lucite
piece and after the crystals were wired in parallel, electrical
wire pigtails were left for subsequent connection to the common
conductors (WD-1TT). The metal end plates were then affixed
employing the threaded rod and epoxy cement.

2. Array Spacing

   This towable array, sometimes referred to as a "snake" in
its seismic use, is used in conjunction with a sound generator.
The frequency of this source dictates the spacing of the individual
hydrophone elements within the overall array. Figure 12 shows
the manner in which the source and array were used for continuous
seismic profiling.

   The individual hydrophone elements, arranged in their spaced
positions, were laced in position with the signal corps wire which
served as the parallel conductors between hydrophones. The wire
also facilitated the spacing of the units and the subsequent insertion
of this assembly into its neoprene casing.

   After the pigtails from the hydrophones were soldered to the two
conductors, the entire hydrophone array was ready for insertion
into the neoprene outer jacket.

3. Applying Neoprene Jacket

   To facilitate inserting the wired array inside the neoprene tube,
the latter was lubricated on the inner wall with the same trans-
former oil which was used as the filler liquid in the final as-
sembly.

A fitting was applied to the end of the tubing and compressed
air was employed to inject the individual hydrophone elements
into the tubing.

4. Oil Filling

The oil used for this purpose was a high dielectric transformer
oil.[13] After the hydrophone elements were located in their
respective positions in the neoprene jacket, the metal tail piece
was secured in place. The fore-end of the array was elevated
and oil filled. (It is important that the units be manipulated to
be sure that all air within the tube is replaced by the oil. The
metal nose piece, affixed to the cable, is then located and secured.)

C. Transformer Coupling

An impedance converting transformer was also incorporated into the
"snake," and the towing output cable was attached to the low impedance winding
of the transformer. A matching transformer was used preliminary to the read-
out equipment.

D. Typical "Snake Design"

One of the towable arrays constructed for continuous seismic profiling
experimentation consisted of thirty-two acceleration-balanced hydrophone
elements wired into the 4000-ohm winding of a G53 TRIAD geoformer. The
500-ohm output of the transformer was connected to the two-conductor electrical
cable which in turn was fed into a matching transformer, and thence to the
final data recording instrumentation. The overall length of this array was 150 ft.

---

[13] See Appendix "Material Sources."

Since the array tended to whip when towed, a 10-ft length of $\frac{1}{2}$-in. nylon line was fastened as a damper to the tail piece of the array.

E. Other Modifications Incorporated into the Towed Array

For purposes of ascertaining the depth of water at which these arrays were being towed, some units had a pressure gauge incorporated into the design. Some efforts are now being exerted to incorporate a transponder into the array configuration. If successful, this transponder will indicate array distance from the bottom, or from the surface in the case of shallow towing.

VI HYDROPHONE INCORPORATING
IMPEDANCE MODIFYING TRANSFORMER

A. Background

A hydrophone using cylindrical piezoelectric elements large enough to encompass a small transformer was constructed for a particular experiment and has since proved successful as an all-purpose detector when extremely high signal gain is not vital. Figure 15 shows details of this hydrophone.

B. Construction

The two cylindrical piezoelectric elements were series wired and cemented together with epoxy plastic. The transformer (TRIAD #G101) was wired to supply a 145-K ohm to a 500-ohm impedance ratio. The metal end plate accommodating the feed-through compression gland was wired, and these wires were soldered to the low impedance side of the transformer. The previously cemented cylinders were then arranged to enclose the transformer in the lower half of the two assembled cylinders. A dowel of epoxy plastic

-31-

SIGNAL WIRE

SEAL GLANDS

CLAMPING WIRE

NEOPRENE SLEEVE

PZT5-CYLINDER 1.5" O.D. X 2.25" LG. .125" WALL

NEOPRENE BOOT

GEOFORMER #G101

END PIECE
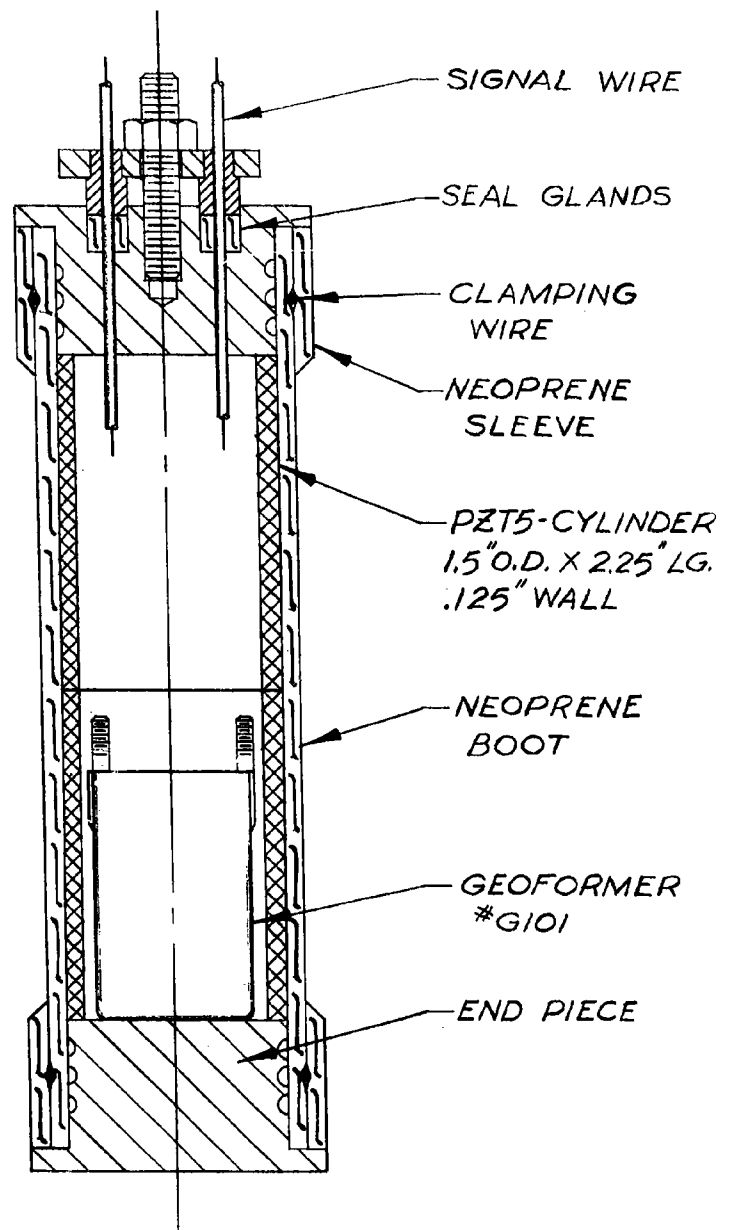
HYDROPHONE WITH BUILT-IN TRANSFORMER

Figure 15

was placed in the upper half of this cylinder after the cylinder assembly was wired to the high side of the transformer. After this assembly was fitted with the neoprene jacket as indicated in Fig. 15, the entire unit was filled with epoxy plastic. After all bubbles had time to be liberated, the other metallic end piece was placed in the assembly and both ends of the neoprene tube were secured with a copper wire. The wire was protected by neoprene sleeves made from the same neoprene tubing.

C. Testing and Calibration

In the course of testing and calibrating this hydrophone, an equivalent matching transformer must be used to preserve the inherent characteristics of the hydrophone.

VII MISCELLANEOUS DEVELOPMENTS IN THE HYDROPHONE FIELD

A. Fuel Tank Hydrophone

A transformer-coupled acceleration-balanced hydrophone was installed in one of the fuel tanks amidship the USNS Gibbs. This was used specifically for recording shot arrivals while the ship was underway.

1. Description

Details of construction are shown in Fig. 16A and the method of suspension in the fuel tank is shown in Fig. 16B. A heavy jacketed neoprene two-conductor electrical cable was fed through the clean out plate of the tank by means of a compression gland fitting. The diesel oil tank into which the hydrophone was placed was located between ship frames Nos. 45 and 50.
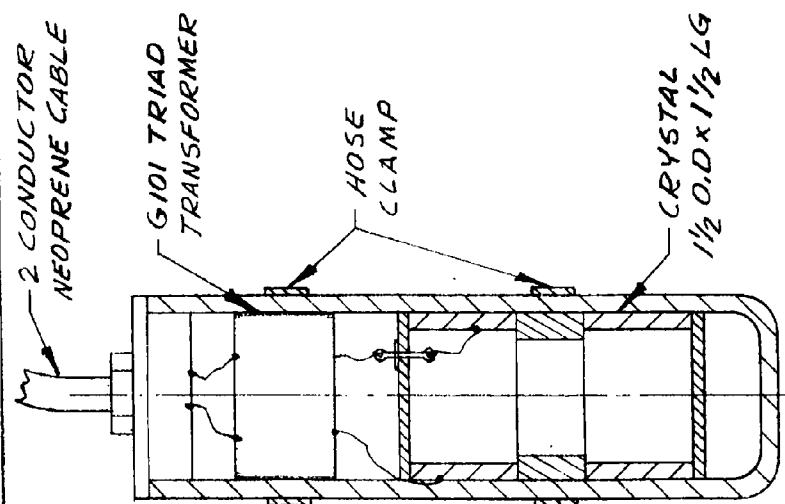
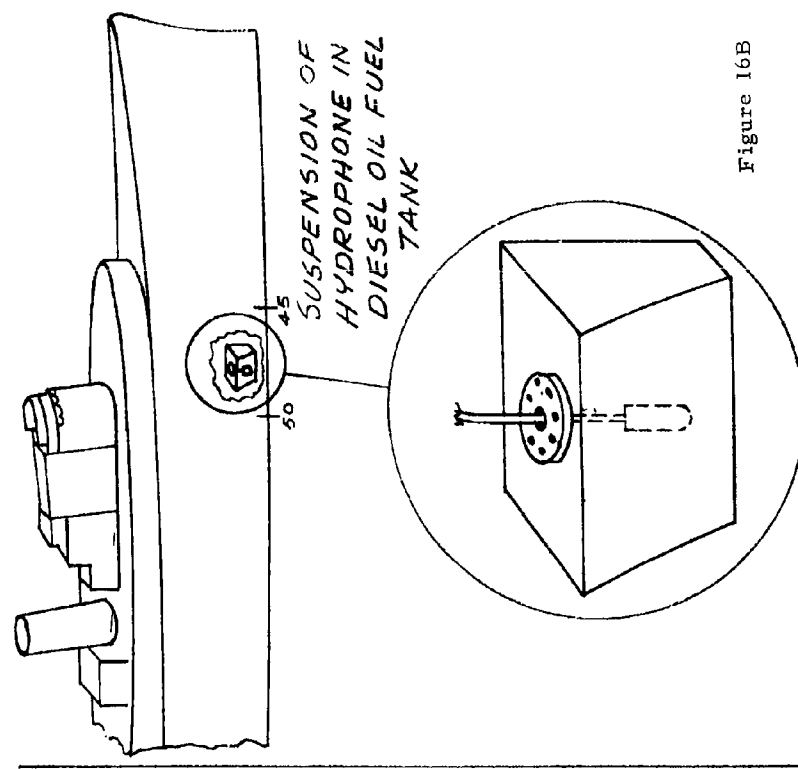SUSPENSION OF HYDROPHONE IN DIESEL OIL FUEL TANK

+5

50

Figure 16B

2 CONDUCTOR NEOPRENE CABLE

G101 TRIAD TRANSFORMER

HOSE CLAMP

CRYSTAL 1½ O.D. x 1½ LG

Figure 16A

FUEL TANK HYDROPHONE

-34-

2. Value of Tank-Mounted Hydrophone

A towed hydrophone with its inherent difficulties of chafing cable, noise, and associated problems was normally used for recording explosive charges. In the course of operation of the tank-mounted hydrophone, using a 4-lb tetryl charge with an 18-in. fuse in a water depth of 15,000 ft made it possible to record the fourth bottom bounce while the ship was traveling at a speed of 10 knots.

B. Hydrophones with Built-In Preamplifier[14]

Two types of hydrophones with built-in preamplifiers are being developed. One design consists of a metal vessel for the preamplifiers, which fits into the cylindrical piezoelectric element, to protect the preamplifier. The second design eliminates the need for this protecting container by using electrical components selected for their ability to withstand 10,000-lb psi hydrostatic pressure. These units are surface powered, but some of the refinements of the preamplifier design are still being developed. The use of field effect transistors in the design of a high input impedance transistorized circuit has opened up the possibility of pursuing this present design by scribing and series wiring the electrodes of the cylinders, thereby more fully utilizing the inherent piezoelectric potential of the elements.

1. Hydrophone with Pressure-Protected Preamplifier

Details of this hydrophone are shown in Fig. 17. The hydrophone utilizes a 2-in. outside diameter, piezoelectric cylinder. The preamplifier in this particular unit is contained in a metal

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[14] The electronic phase of this program at Hudson Laboratories was performed by Mr. Thomas Pappas and Mr. Leslie Mike.

MECCA SEAL

TOP PIECE

"O"- RING

AERO SEAL CLAMP

ELECTRONICS CASE

ELECTRONICS

THREADED ROD

AERO SEAL CLAMP

ADJUSTING PIECE

CRYSTAL

BOOT

OIL

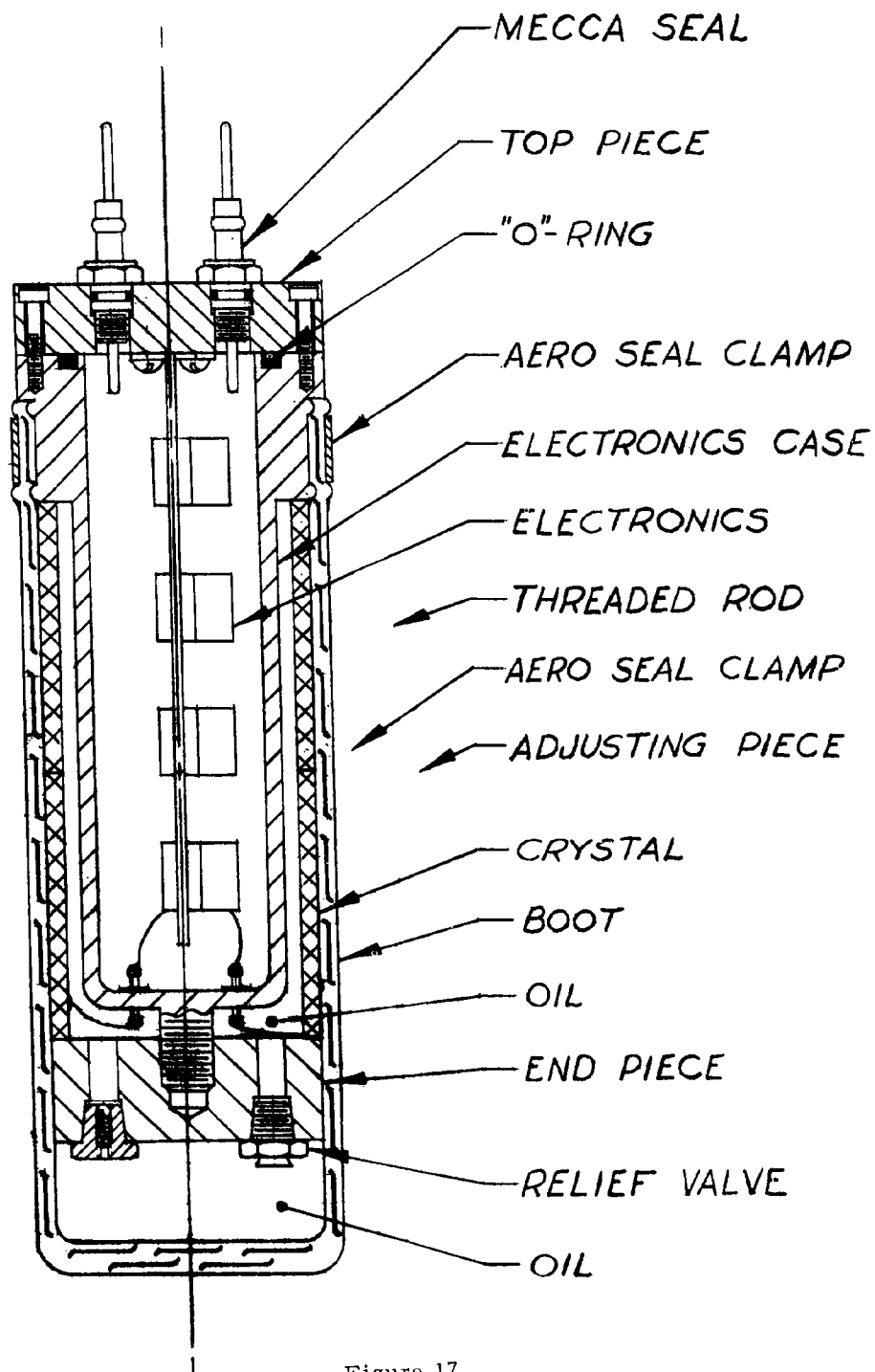END PIECE

RELIEF VALVE

OIL

Figure 17

case within the cylinder and this has the advantage of being removable for trouble shooting or modification.

2. Hydrophone with Free-Flooding Preamplifier–Fig. 18

   This design of hydrophone and preamplifier combination was possible because certain electronic components, capacitors, resistors, and transistors are unaffected by excessively high hydrostatic pressure.[15] In this construction the preamplifier was mounted within the piezoelectric cylinder and secured to the rod which joined the end plates of the hydrophone. A 2-in. outside diameter cylinder was employed and afforded sufficient space for the transistorized preamplifier.

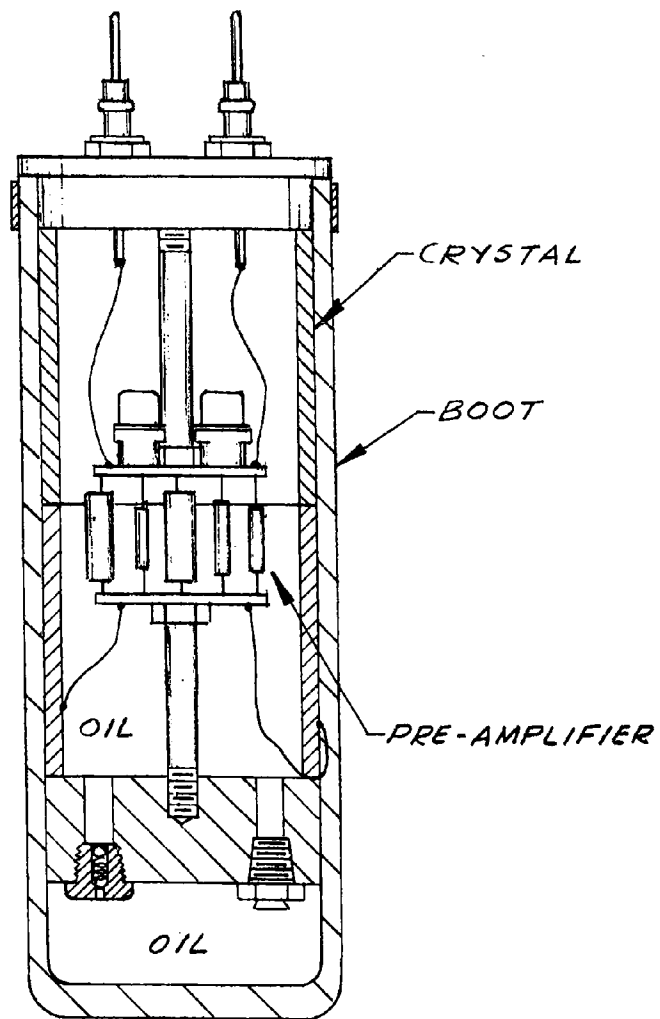3. Advantages of Hydrophone–Preamplifier Combination

   a. Cable Mounting

      Either design of hydrophone-preamplifier combination is a much smaller assembly than the separate preamplifier case and hydrophone previously used, and simplifies the problem of mounting the unit to a supporting cable.

   b. Acceleration-Balancing

      Utilizing the type of mounting shown in Fig. 19, the hydrophone and preamplifier units are acceleration balanced and shock mounted, thereby doubly insuring against noise due to cable motion.

---

[15] Work related to this problem is reported by C. L. Buchanan of NRL in the June 1961 Progress Report, Putting Pressure on Electronic Circuit Components.

CRYSTAL

BOOT

OIL

PRE-AMPLIFIER

OIL

HYDROPHONE WITH
FREE-FLOODING PRE-AMPLIFIER

Figure 18

MULTI-CONDUCTOR
STRAIN-CABLE

LORD
MOUNT

LORD
MOUNT

CABLE MOUNTED HYDROPHONE
PRE-AMPLIFIER COMBINATION

Figure 19
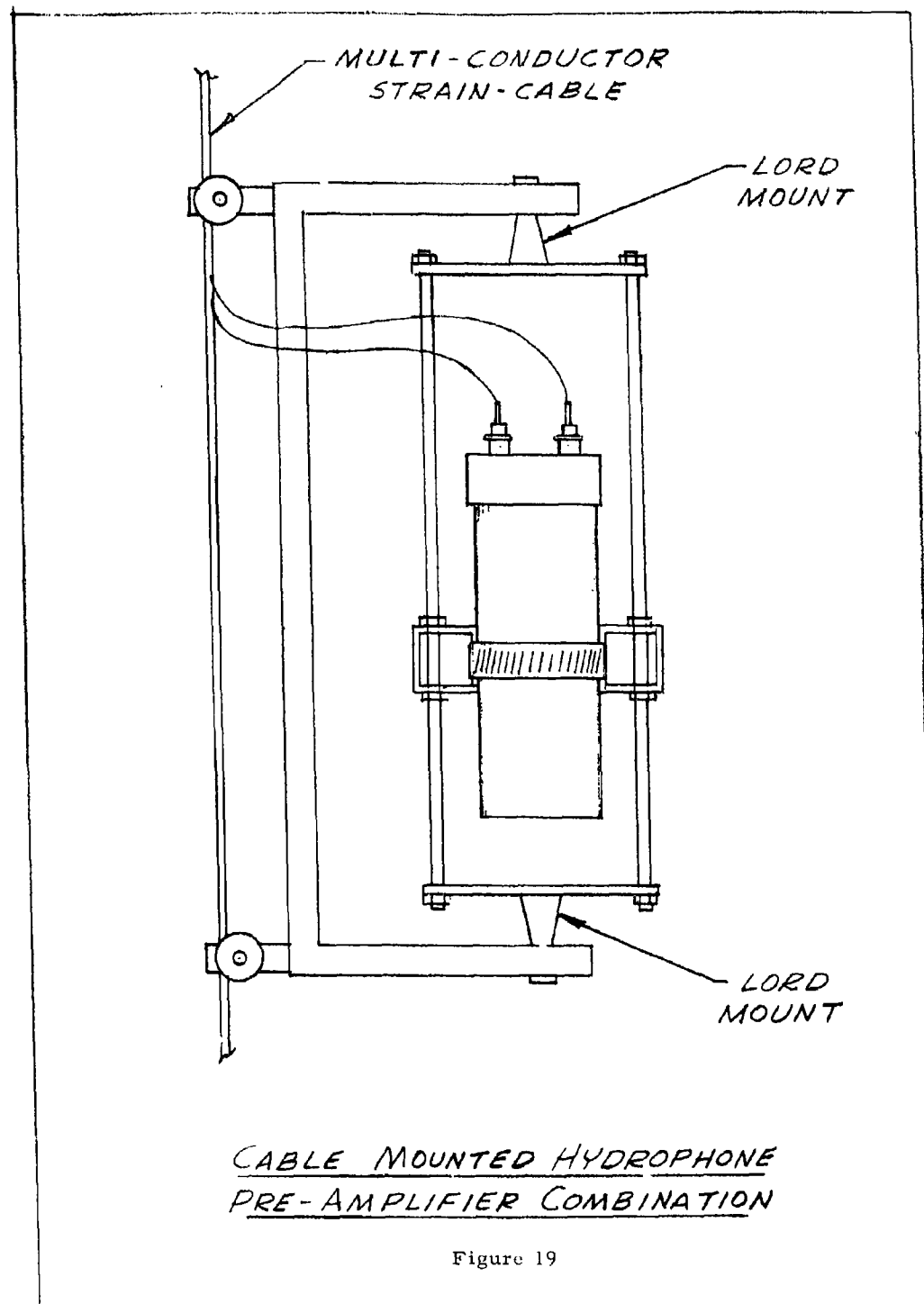
VIII ASSOCIATED DEVELOPMENTS

A. Rapid Calibration Tank-Fig. 20

Collateral with the research and experimentation in the course of the development of the high pressure hydrophone described earlier, a rapid comparative hydrophone evaluator was developed.

1. Description of Test Unit

This testing device used a standard hydrophone for comparison with the unit to be tested. The two hydrophones were placed in a sealed tank of water in which the level of water was maintained at a uniform height. A prescribed pressure of air (15 lb psi) was applied to the surface of the water, subjecting both hydrophones to a hydrostatic pressure and generating an electrical charge. With the sudden release of this air pressure the individual electrical outputs were read on an oscilloscope and the relative merits of the test hydrophone were compared with the standard.

2. Features of Design

a. For simplicity of operation a three-way solenoid valve was used. A regulated air supply was connected to the outlet of the valve which upon excitation by means of a double pole, double throw switch allowed the flow of this air to the upper section of the test tank. Upon release of the switch, this air pressure was released from the tank through the same solenoid valve.

b. For uniform test conditions the water level in the tank must be the same at all times during the testing. The use of a leveling bottle simplifies this operation.
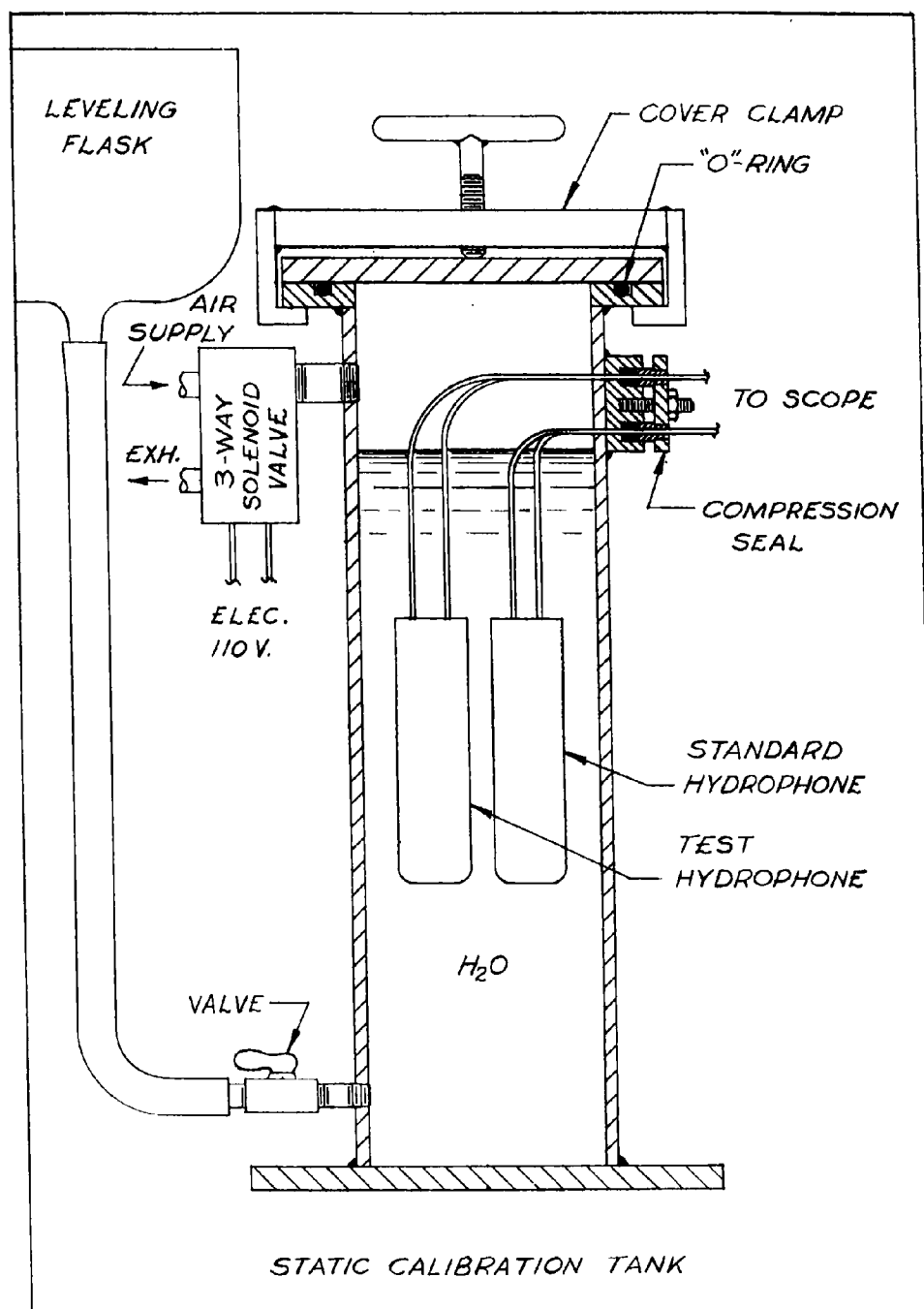
-40-

Figure 20

c. In those cases where extreme variations existed in the capacity of the test and the standard units, spurious results were encountered. A resistor (22 megohm) was placed in series with one of the leads leading from the test tank to the oscilloscope, thereby subordinating the influence of the capacitive variations in the two hydrophones.

B. Test Chamber for Hydrophone Low Frequency Cutoff Study

The oil-filled pressure-balanced hydrophone was designed for very low frequency listening. Varying such parameters as capillary dimension or oil viscosity low frequency signals could be mechanically rejected where desirable. The formula for low frequency cutoff has been presented earlier in this report.

To verify empirically the results of such design modifications, a tank was constructed using an oscillator-controlled, heavy duty, low frequency speaker (Jensen 12" Woofer Flexair speaker No. 71-DX-104-J) to vary the hydrostatic pressure field into which the experimental unit was placed.

1. Description of Unit

This test tank (Fig. 21) was mounted in a table isolated from vibration by means of Lord shock mounts. Some mechanical dampening of the entire assembly by metal stiffeners was necessary to eliminate the interference of low frequency building vibration and inherent mechanical resonances of the overall assembly.

2. Test Procedure

After modification and assembly the hydrophone under investigation for low frequency cutoff is placed in the test tank alongside a standard hydrophone. The standard is used as a control to assure uniform energy from the speaker driver as the studied hydrophone is sub-
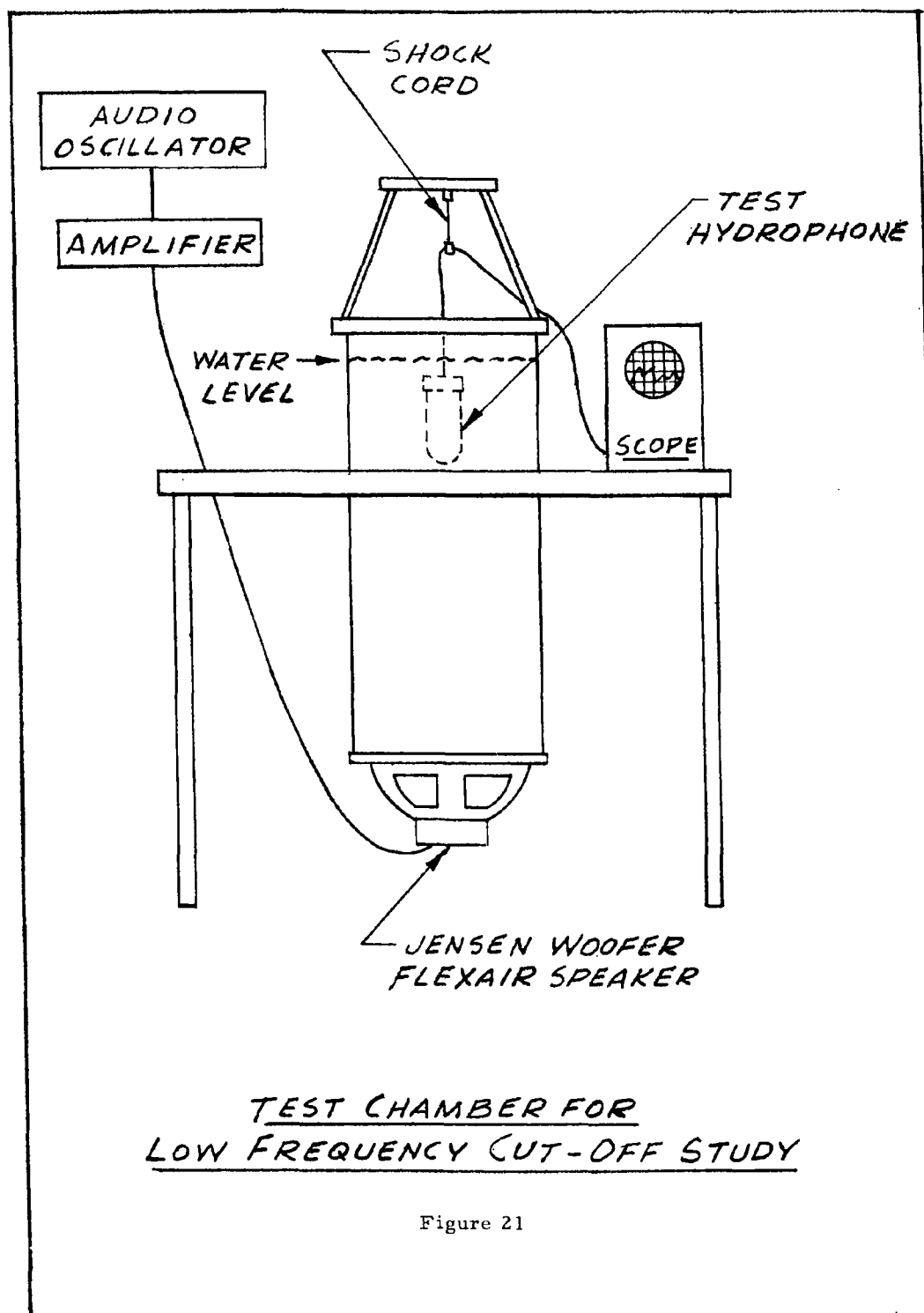
TEST CHAMBER FOR
LOW FREQUENCY CUT-OFF STUDY

Figure 21

jected to varying frequencies. A curve plotting frequency vs voltage output will disclose that frequency at which the electrical energy declines.

C. Vibration Table Used In Acceleration Balancing of Hydrophones

This "shaker table" was developed during the initial investigation of the advantages of a hydrophone design which would minimize the undesirable influence of vertical motion.

1. Description of Vibration Table

Figure 22 shows how the active element was mounted into a table assembly, offering a convenient support for the elements under study. The vibration element is an electrical driver made by the MB Manufacturing Company, New Haven, Connecticut. The frequency is controlled by an amplified signal generator output.

2. Testing Procedure

As mentioned before under "Balancing Procedure," the hydrophone is balanced at a frequency of 100 cycles and at an accelerative force of 1 g. These controls or limitations were chosen because most of the influence of accelerative motion, particularly due to cable motion, was determined to be below 100 cycles.

In the earlier acceleration-balanced hydrophone designs, in which a pair of cylinders were mounted on either side of a supporting plate, no actual final hydrophone adjustment was possible. The relative merits of this type of mounting with respect to a non-inertial balanced hydrophone could, however, be evaluated with this shaker table. The later designs (Figs. 9, 12, and 13) permitted a more precise balancing operation, and it was here that the shaker table

-44-
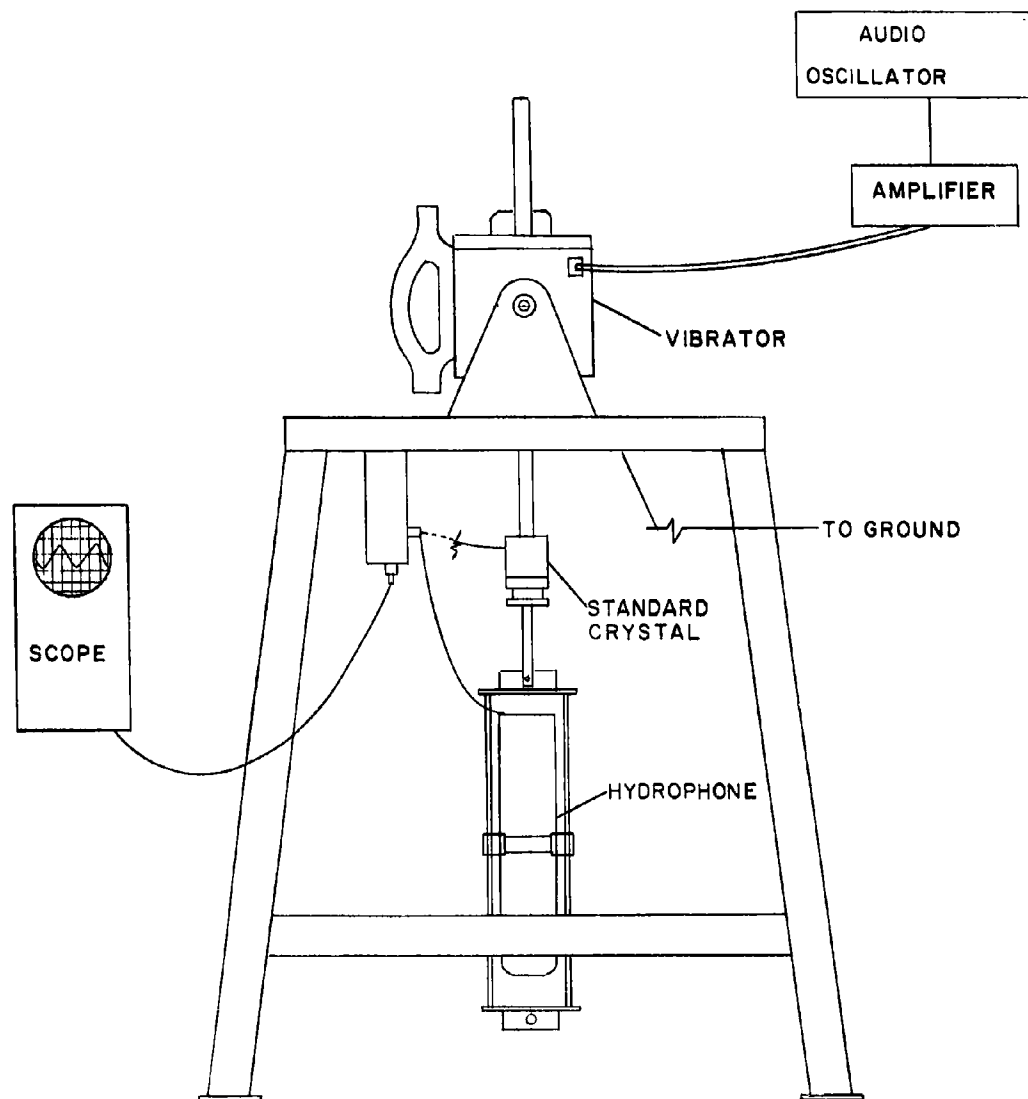
HYDROPHONE VIBRATION ANALYZER

Figure 22

was necessary for the accurate location of the hydrophone with
respect to its mounting position to achieve a minimal influence
due to accelerative motion.

In certain cases where the hydrophone and mounting equip-
ment were somewhat heavy for the normal rating of the vibrator,
a compensating spring was applied above the armature shaft
having an adjustment to keep the armature centered with respect
to the field coil.

IX AREAS FOR FUTURE INVESTIGATION IN THE HYDROPHONE FIELD

A. Low-Frequency Cutoff

More experimental work is needed to prove empirically the equation
for low-frequency sensitivity cutoff. Rejection of signals below the threshold
of interest will probably be most beneficial in eliminating cable noise in
vertically mounted and towed listening systems.

B. Disc Piezoelectrics

The use of discs for hydrophones must be investigated further.
Preliminary experiments have shown the importance of this piezoelectric
geometrical shape. A high sensitivity is achieved by using the shear mode
of stress of two laminates of piezoelectric material (bimorphs). A deflection
of this type of unit produces greater sensitivity because one half of the "bi-
laminate" is in tension while the other half is in compression, resulting in
greater additive mechanical stress. For shallow application, two bilaminates
mounted on either end of an air-filled cylinder are very satisfactory. For

deep water use, however, where the pressure balancing technique is employed, the greater disc deflection necessary for adequate signal requires an extremely high fluid compliance attainable only by large volume since the bulk modulus of oil has its limitations.

$$C = \frac{V}{B} \quad ,$$

where

C = Compliance of oil

V = Volume of oil within hydrophone

B = Bulk modulus of oil .

C. Hydrophone Preamp Combinations

At Hudson Laboratories only preliminary investigation has been made in developing this combination package. Further development of the free flooding preamplifier, particularly one which is surface powered without the attendant problem of cross talk, is necessary before a fully acceptable design is achieved.

D. Mechanical Amplification

Some preliminary, inconclusive experiments have been conducted using a single cylindrical piezoelectric element with affixed end plates, the entire assembly being placed in a large metal cylinder. The calibration of this device suggested a design of hydrophones by which greater use of such stress amplification might be pursued. Using the bimorph disc piezoelectric and a design employing such mechanical advantage, hydrophone sensitivity might be much improved.

E. Fuller Utilization of Piezoelectrics

Using the preamplifier to incorporate the field effect transistor (FET) makes higher (low voltage drain) input impedance circuits possible. Multiple ring electrodes might thus be made on a single piezoelectric cylinder and series wired, thereby utilizing to the maximum degree the inherent potential of the piezoelectric.

APPENDIX A

Comparison of Barium Titanate and Lead Zirconate Titanate

The properties of two piezoelectric materials relative to their appli-
cation in the hydrophone field are considered. For convenience of presentation,
Clevite materials Ceramic "B," a modified barium titanate material, and PZT-5,
a lead zirconate titanate composition, are compared. These materials have
typical properties for equivalent materials of other manufacturers.

A. Piezoelectric Constants

"g" constants: The "g" constant can be defined as the open circuit
field developed by the material for a measured applied stress. This constant
is expressed in the following equation.

$$g = \frac{\frac{v}{t}}{\frac{p}{A}}$$

where

$\quad\quad\quad v =$ output voltage

$\quad\quad\quad t =$ distance between electrodes in meters

$\quad\quad\quad p =$ force in newtons/meters^2

$\quad\quad\quad A =$ area of stressed surface in meters.^{2}

The "g" constant is designated by subscripts such as g_{ij} in which the first
indicates the direction of polarization and the second the direction of stress.

g_{31} means that the stress is applied perpendicular to the direction of polarization, while g_{33} means both polarization and stress directions are parallel.

	Ceramic B	PZT-5
g_{31}	$-5.5 \times 10^{-3} \frac{\text{volt meter}}{\text{newton}}$	$-11.4 \times 10^{-3} \frac{\text{(v-m)}}{\text{n}}$
g_{33}	$14.0 \times 10^{-3} \frac{\text{(v m)}}{\text{n}}$	$24.8 \times 10^{-3} \frac{\text{(v m)}}{\text{n}}$

As discussed in a later section, the most significant piezoelectric constant applicable to cylindrical materials for sensing devices is the g_{31} constant.

B. The Coupling Coefficient

The coupling coefficient is referred to as the "k" factor and is a measure of the ability of a piezoelectric ceramic to change energy from one form into another.

$$k^2 = \frac{\text{Electrical energy stored in piezoelectric}}{\text{Mechanical energy supplied}}$$

In actual use, the square root or "k" is used to indicate the coupling quality of the material. The "k" factor can be determined experimentally by ascertaining the resonant frequency (f_r) and the antiresonant frequency (f_a) of the material. This is obtained by recording the maximum and minimum voltage output which results from driving the transducer material through the spectrum of frequencies. Using these determined values of f_a and f_r , a close approximation to the square of the coupling coefficient can be computed from the following equation:

$$k^2 = \frac{\pi^2}{4} \cdot \frac{f_a - f_r}{f_r} \qquad^{16} .$$

The values for the coupling coefficients of interest are:

	Ceramic B	PZT-5
k_{33}	.48	.71
k_{31}	.19	.34

As above, the first subscript refers to the polarization axis and the second to the stress axis.

C. Curie Point

In the design of acoustic detectors, the active element must be used well within the upper and lower curie points of the material. If the temperature of use exceeds the upper curie point the element loses polarization and its piezoelectric property. At the lower curie point, there is a rapid variation in the piezoelectric characteristics (Ceramic B).

	Ceramic B	PZT-5
Upper curie point	115°C	365°C
Lower curie point	0°C	-300°C

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[16] Theodor F. Heuter and Richard H. Bolt, Sonics (John Wiley & Sons, Inc., New York, 1955), p. 119.

D. Density

Besides the mechanical effect of high density (allowing higher com-
pressive strength), the electrostrictive properties of the material are
influenced by the density of the piezoelectrics.

	Ceramic B	PZT-5
Density	5,600 kg/meters^3	7,700 kg/meters^3

E. Free Dielectric Constant

The dielectric constant and the geometry of the piezoelectric determine
its electrical capacity. In the computation of capacity in the following equation
K   is the dielectric constant.

$$C = \frac{.224\ KA}{t} \quad ,$$

where

$\quad$ C = capacity in $\mu\mu f$

$\quad$ K = dielectric constant (free)

$\quad$ A = area of smaller electrode surface (in^2)

$\quad$ t = distance between electrodes (in.)

$\quad$ .224 = permitivity of free space (using measurements
$\qquad\qquad$ in inches)

	Ceramic B	PZT-5
dielectric constant K	1200	1700

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APPENDIX B

Source of Material

Suppliers of the various materials used in hydrophone construction
at Hudson Laboratories are listed. Where possible, several sources of
supply are suggested. However, the list is by no means complete nor is
relative evaluation intended.

1. Piezoelectric Cylinders and Discs

Channel Industries, 839 South Kellogg Ave., Santa Barbara, Cal.

Clevite Electronic Components, 232 Forbes Rd., Bedford, Ohio

Electra Scientific Corp., Electra Way, Fullerton, Cal.

Electro Ceramics, 2645 South 2nd West, Salt Lake City, Utah

General Instrument Corp., 65 Gouverneur St., Newark, N. J.

Gulton Industries, Metuchen, N. J.

Minneapolis Honeywell Co., 1885 Douglas Dr., Minneapolis 22, Minn.

Sprague Electric Co., North Adams, Mass.

U. S. Sonics Corp., 84 Sherman St., Cambridge, Mass.

Universal Dynamics Corp., 130 Los Aguojes Ave., Santa Barbara, Cal.

2. Silicone Oil - D. C., 200-350 Centistokes (or equivalent)

Dow Corning Corp., Midland, Mich.

General Electric Corp., Waterford, N. Y.

Union Carbide Chemical Corp., 100 E. 42nd St., New York, N. Y.

3. Transformer Oil - Dial AX

Shell Oil Co., New York, N. Y.

4. Molded Neoprene Boots – In the case of molded boots the mold
was owned by Hudson Laboratories and was made available to
the molding company for completion of the order.

Goodrich Rubber Co., Akron, Ohio

U. S. Hydro Tech. Co., 16 W. 22nd St., New York, N. Y.

5. Neoprene Tubing

Minor Rubber Co., Bloomfield, N. J.

6. Capillary Tubing

Anaconda American Brass Co., Small Tube Div., Waterbury 20, Conn.

Superior Tube Co., Norristown, Pa.

7. Pressure Relief Valves

Alemite Corp., 1826 Diversey Parkway, Chicago 14, Ill.

Lincoln Engineering Co., 4010 Goodfellow Blvd., St. Louis 20, Mo.

8. Epoxy Resin – Plastic HT 304 – Activator HT 101

Hytemp Resin Co., Stamford, Conn.

9. Polyurethane Molding Materials

Coast Pro-Seal Corp., 2235 Beverly Blvd., Los Angeles 57, Cal.

Products Research Corp., 2919 Empire Ave., Burbank, Cal.

10. Electrical Wire

Wire for interwiring hydrophone crystals – Tensolite No. 1482A –
Tensolite Insulated Wire Co., Inc., West Maint St., Tarrytown, N. Y.

Demolition Cable – used for towable array – U. S. Naval Supply

Signal Corps wire – WD-ITT – secured through U. S. Naval Supply

11. Power Element for Vibrating Table – Model SDA

MB Manufacturing Co., Div. of Textron Inc., New Haven, Conn.

12. Solenoid Three-Way Valve

   R. G. Lawrence Co., Inc., 124 Summit St., Tenafly, N. J.

   A. Schrader & Sons, Div. of Scovell Mfg. Co., 471 Vanderbilt Ave.
   Brooklyn 38, N. Y.

13. Test Tank Speaker Element

   Model C12 - NF 12" Flexair Woofer - Jensen Manufacturing Co.,
   6601 South Laramie Ave., Chicago 38, Ill.

14. Feed-Through Units

   Mecca Cable & Service Inc., Route 4 Box 651, Houston, Texas

   Sealectro Corp., 139 Hoyt St., Mamaroneck, N. Y.

   Stupakoff Ceramic & Mfg. Co., Latrobe, Pa.

15. Lucite Tube & Rod

   Almac Plastic Co., 600 Broadway, New York, N. Y.

   Connecticut Plastic & Supply Co., 630 Broadway, New York 12, N. Y.

APPENDIX C

Calibration Curve and Directionality Patterns for Plastic-Filled Hydrophones

Figures 23-27 represent a broadband calibration and directionality pattern for the hydrophone discussed in II and illustrated in Fig. 1.

Figures 24 and 25 show the directivity pattern of the hydrophone when it is rotated while held in a vertical position. Figures 26 and 27 show its directional sensitivity when rotated in a horizontal position. Since these hydrophones were designed for use in the acoustic range below 2 kc, these curves are presented only for academic interest.
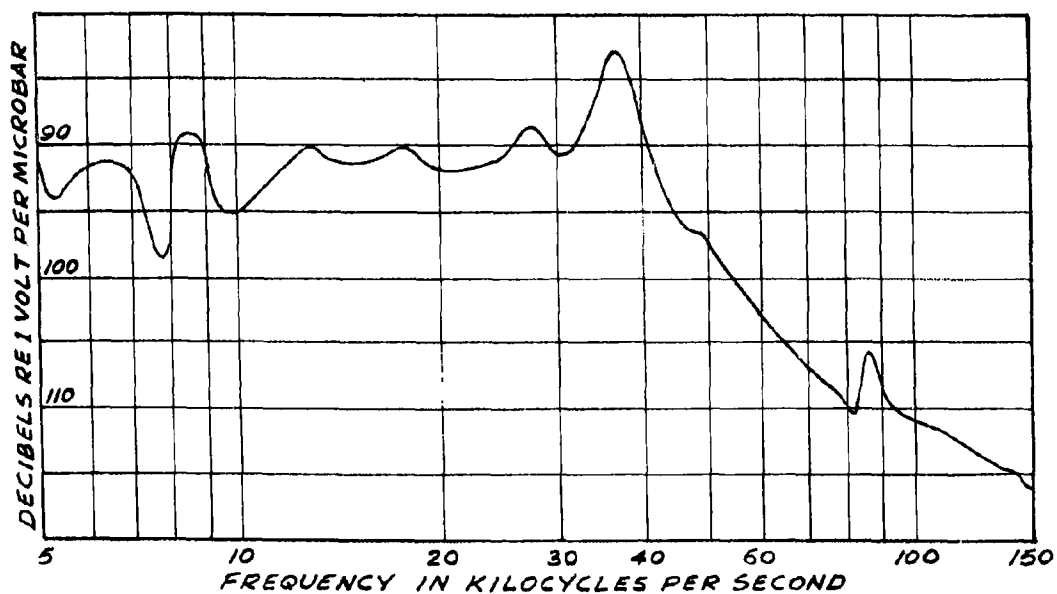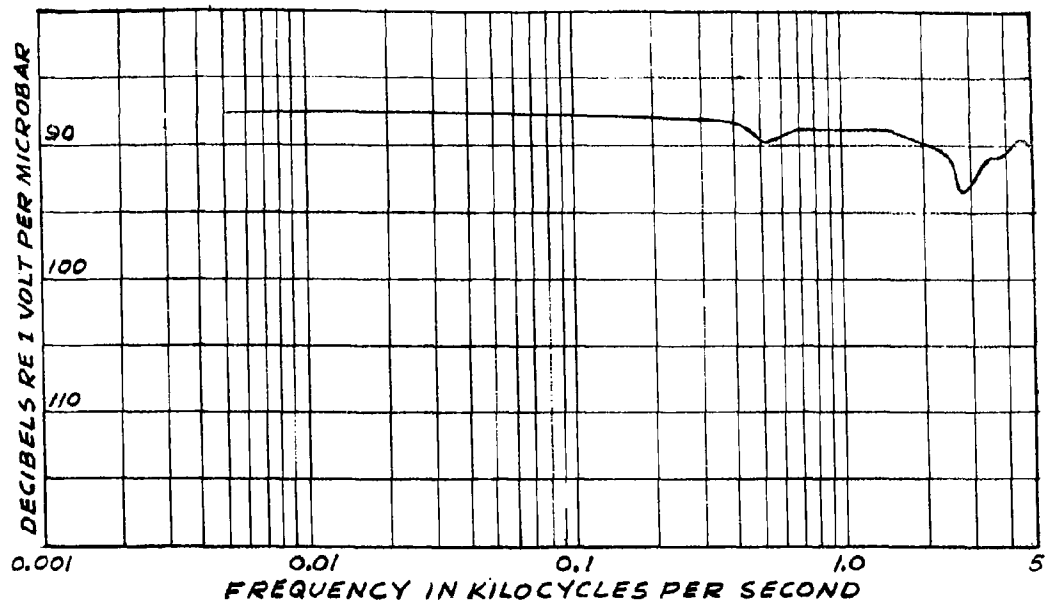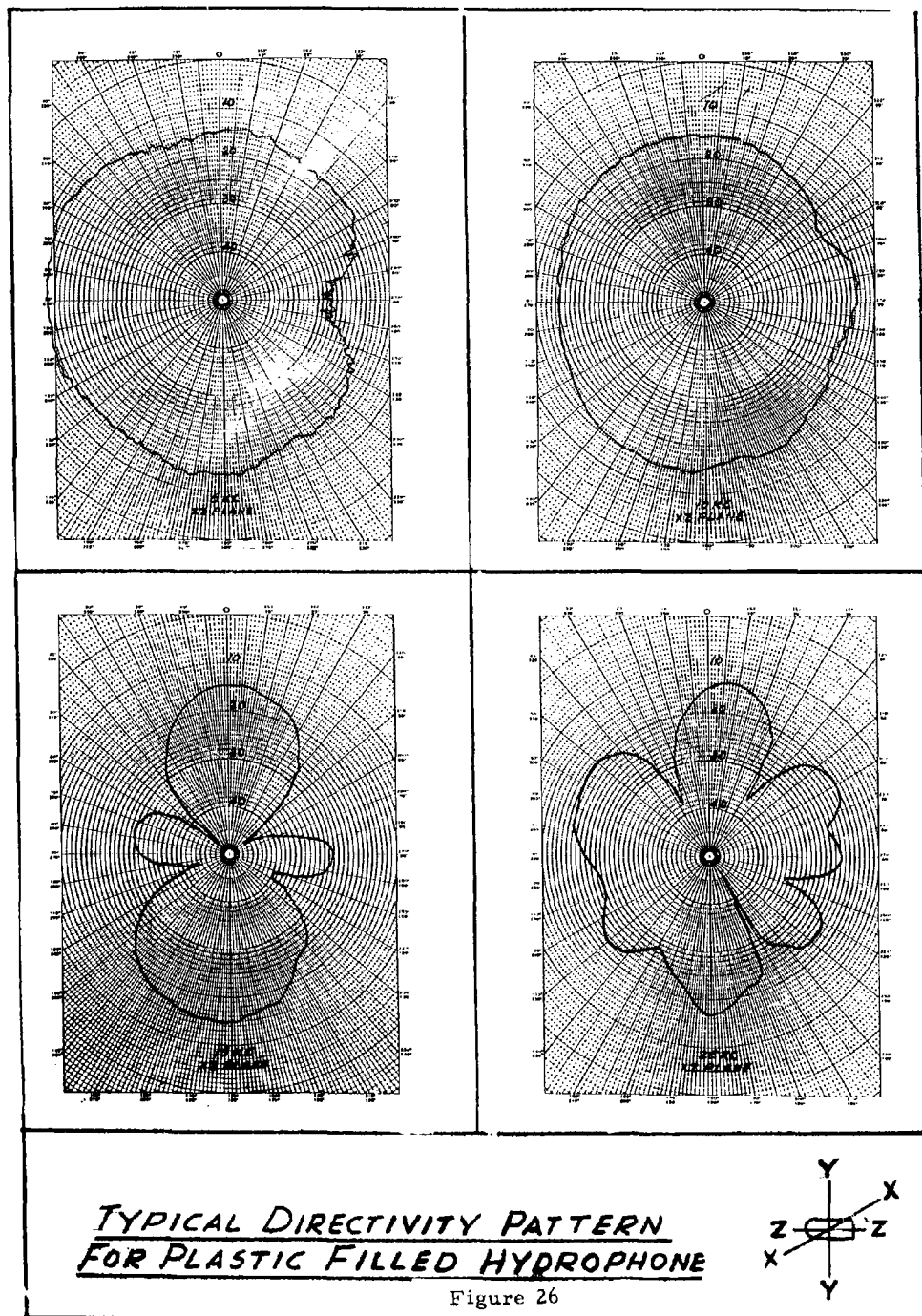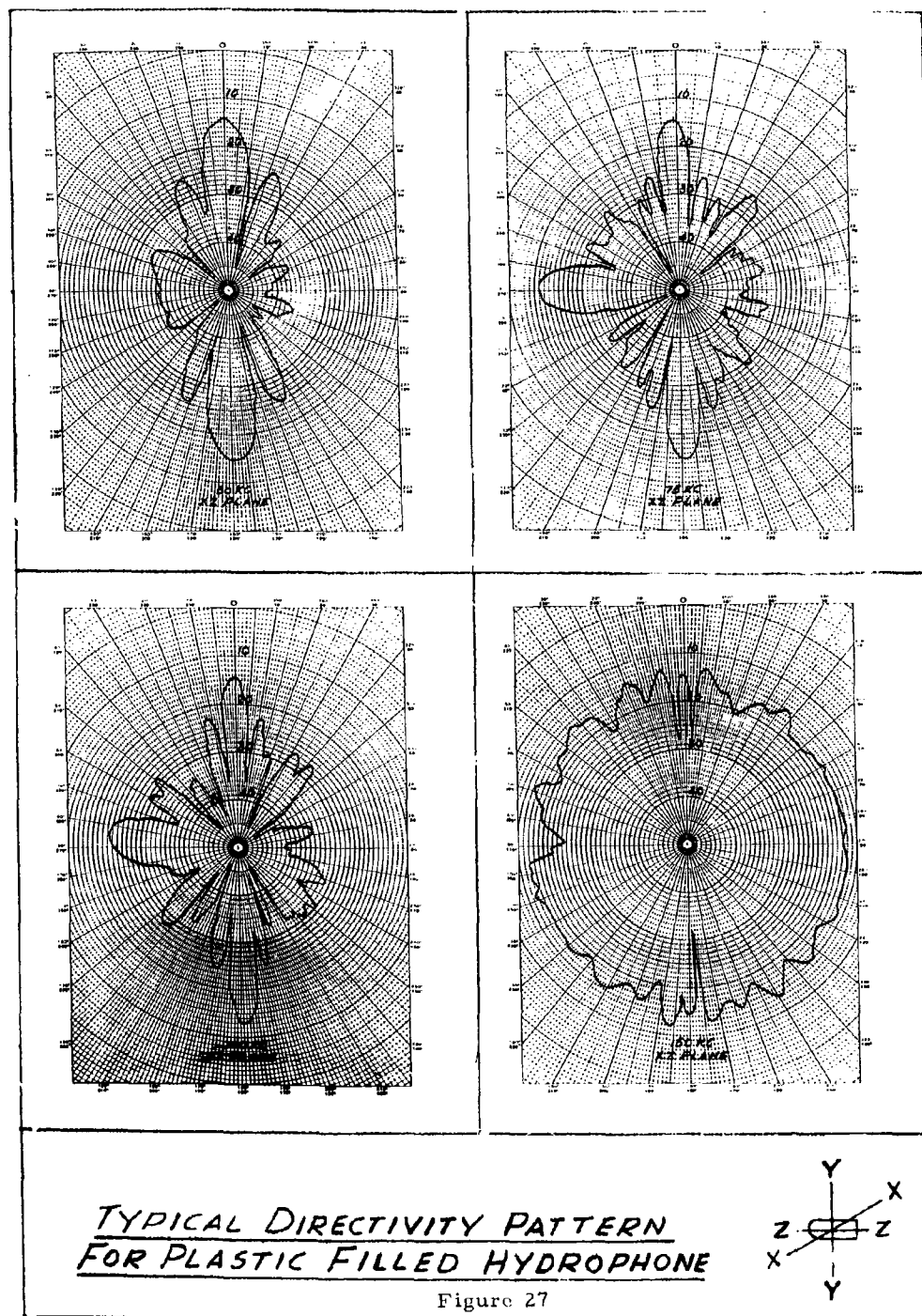
TYPICAL CALIBRATION CURVE
FOR PLASTIC FILLED HYDROPHONE

Figure 23

TYPICAL DIRECTIVITY PATTERN
FOR PLASTIC FILLED HYDROPHONE

Figure 24

TYPICAL DIRECTIVITY PATTERN
FOR PLASTIC FILLED HYDROPHONE

Figure 25

TYPICAL DIRECTIVITY PATTERN
FOR PLASTIC FILLED HYDROPHONE

Figure 26

TYPICAL DIRECTIVITY PATTERN
FOR PLASTIC FILLED HYDROPHONE

Figure 27
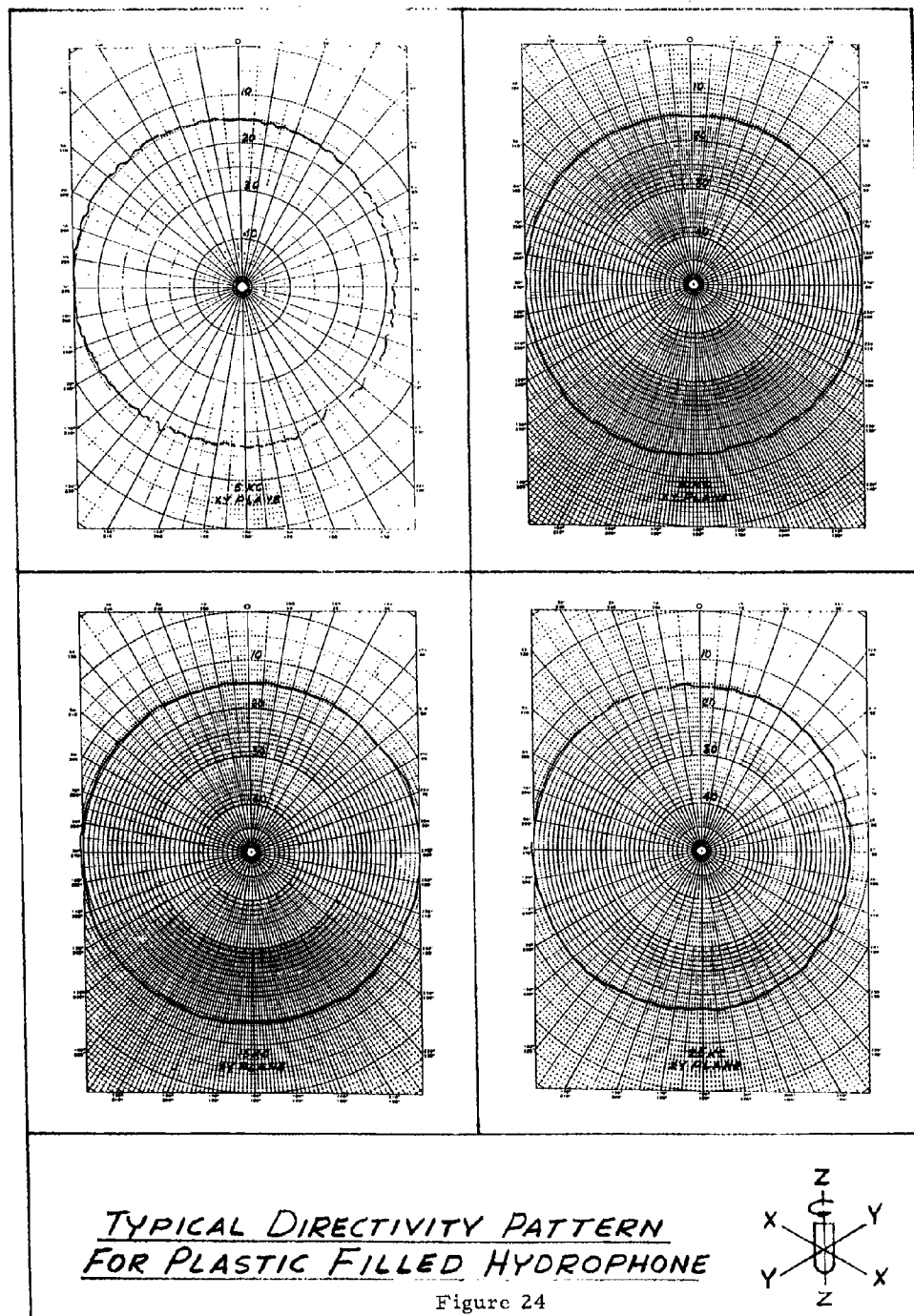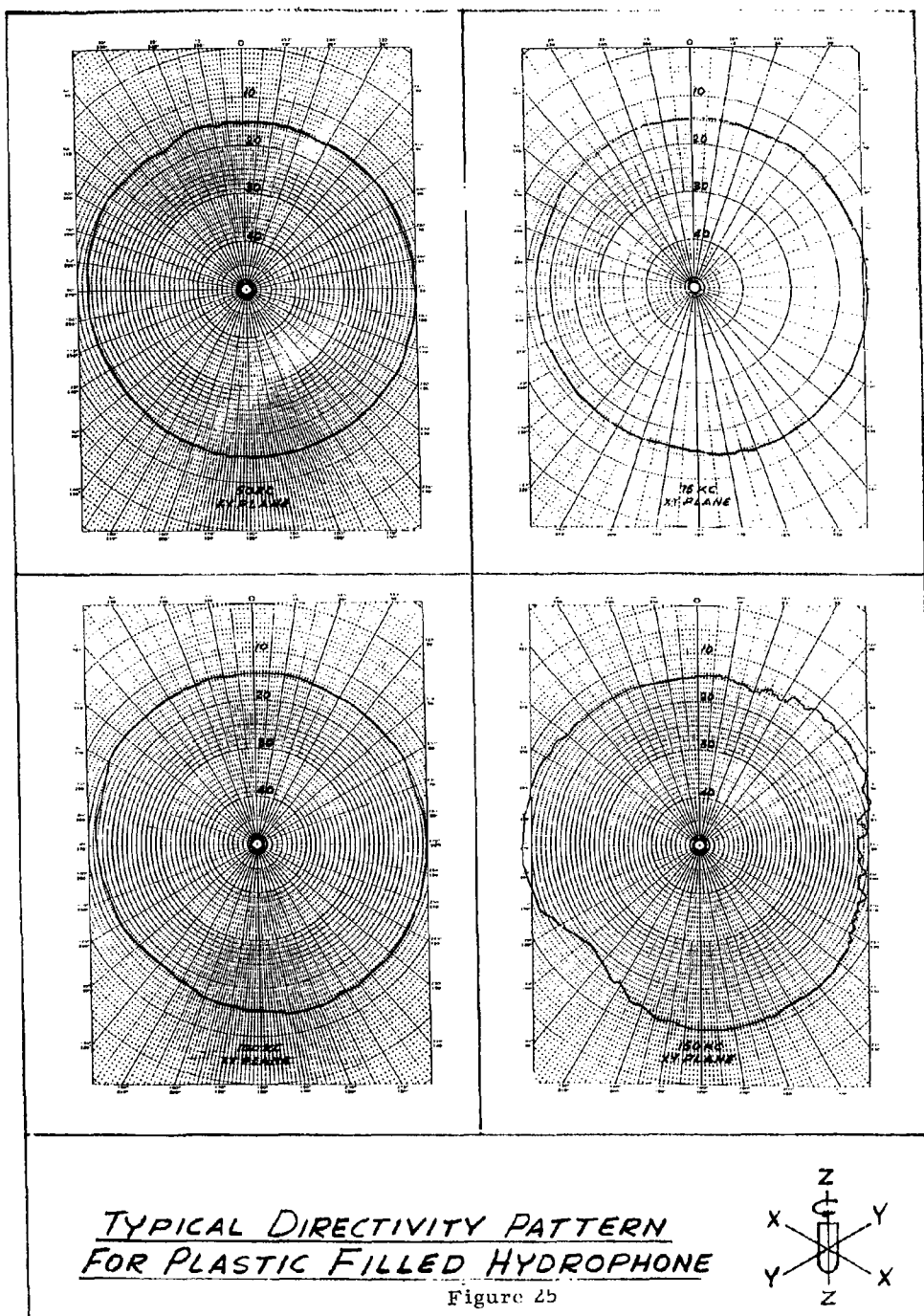
APPENDIX D

Advantage of Cylindrical Construction in Hydrophones

A. Mechanical Stresses

There are three modes of stressing an end-capped piezoelectric
cylinder: circumferentially (hoop), longitudinally, or compressively (thickness).
The voltage generated by the circumferential and the longitudinal stresses are
of the same polarity and hence are additive, but the thickness stress produces
a voltage output of opposing polarity which therefore detracts from the overall
generated electrical energy of the hydrophone. The voltage output of a cylin-
drical hydrophone attributable to each mode of stress application is set forth
below. The cylinder under consideration is one with the inner and outer sur-
faces electroded and polarized radially.

1. Circumferential Stress (Hoop)-Fig. 28A

Since the stress applied is perpendicular to the direction of polar-
ization the piezoelectric g_{31} constant is used to compute the
voltage output.

$$g_{31} = \frac{\dfrac{V}{t}}{\dfrac{F}{A}} \quad \begin{array}{l} \} \text{ or field (volts/meter)} \\ \} \text{ or stress (newtons/meter}^2) \end{array} \quad .$$

Assumptions:

$P = 1$ dyne/cm^2 or .1 newton/$meter^2$

$D = 1.5''$ or $1.5 \times \dfrac{2.54}{100}$ meters

$g_{31} = -11.4 \times 10^{-3}$ volt-meters/newton   .

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Employing the crystal dimensions shown in Fig. 28A and the assumptions given we have:

$$\frac{F}{A} = \frac{p\, D\, \ell}{2\, t\, \ell} = \frac{p\, D}{2\, t} \quad,$$

then

$$g_{31} = \frac{\dfrac{V}{t}}{\dfrac{p\, D}{2\, t}} = \frac{V}{t} \cdot \frac{2\, t}{p\, D}$$

$$V = \frac{g_{31}\, p\, D}{2} = \frac{-11.4 \times 10^{-3} \times .1 \times 1.5 \times \frac{2.54}{100}}{2}$$

$$V = 21.6 \times 10^{-6}$$

Sensitivity (db) $= 20 \log 21.6 + 20 \log 10^{-6} = -93.4$ db .

2. Longitudinal Stress-Fig. 28B

The area of applied force and the area of stress are indicated. With the same conditions and dimensions as the example above, the following applies:

$$g_{31} = \frac{\dfrac{V}{t}}{\dfrac{F}{A}} = \frac{p\, \pi\, \dfrac{D^2}{4}}{\pi\, D\, t} = \frac{p\, D}{4\, t}$$

$$V = \frac{g_{31}\, p\, D}{4} = \frac{11.4 \times 10^{-3} \times .1 \times 1.5 \times \frac{2.54}{100}}{4}$$

$$V = -10.8 \times 10^{-6}$$

Sensitivity (db) $= 20 \log 10.8 + 20 \log 10^{-6} = -99.4$ db .

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3. Compressive Stress--Fig. 28C

In this case, since the stress is applied parallel to the direction of polarization, the g_{33} piezoelectric constant is used. Referring to Fig. 28C we apply the equation

$$g_{33} = \frac{\frac{V}{t}}{\frac{F}{A}} = \frac{p\,D\,\pi\,l}{D\,\pi\,l\,(\text{approx})}$$

$$V = g_{33}\,p\cdot t$$

$$= 24.8 \times 10^{-3} \times .1 \times .125 \times \frac{2.54}{100}$$

$$= 7.9 \times 10^{-6}\ \text{volts}$$

Sensitivity (db) $= 20 \log 7.9 + 20 \log 10^{-6} = 102.1$ db.

B. Observations Concerning Stress Investigations

Relative Merits - The circumferential stress applied to the end-capped piezoelectric cylinder generates double the voltage output of either of the other two stresses. Whereas the circumferential and the longitudinal stresses augment each other, the compressive (thickness) stress produces a voltage of opposite polarity and reduces overall voltage.

Design Note - It is desirable to use cylinders as thin as possible since cylinder thickness adversely influences the voltage output due to mechanical stress. This can best be accomplished by employing the pressure equalization principle already discussed earlier in this report. Much more voltage is put out when the end-capped cylinder is used, due to the stress enhancement the cylinder mechanically permits.

-64-
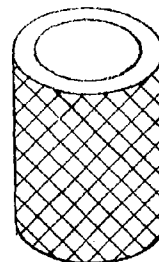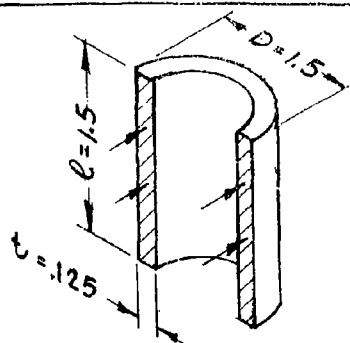
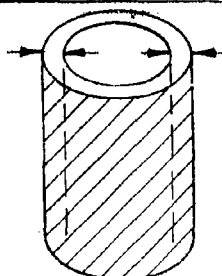STRESS AREA = $2\ell t$ FORCE AREA = $D\ell$
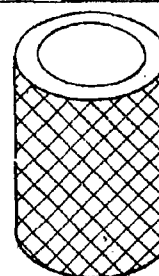
CIRCUMFERENTIAL STRESS

Figure 28A,
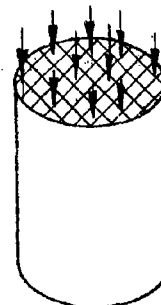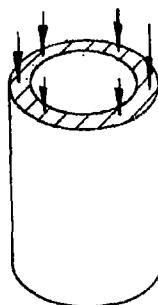
STRESS AREA = $D\pi t$ FORCE AREA = $\dfrac{\pi D^2}{4}$

LONGITUDINAL STRESS

Figure 28B

STRESS
AREA

FORCE
AREA

STRESS AREA = $D\ell$ FORCE AREA = $D\ell$

COMPRESSIVE STRESS

Figure 28C

APPENDIX E

To design a pressure-balanced hydrophone (capillary type) having a sensitivity fallout point at a certain frequency, the following equation (presented in an earlier section of this report) is used

$$f_o = \frac{D^4 B_e}{256 \, \mu \, \ell \, V_e}$$

D = diameter of capillary (in.)

ℓ = length of capillary (in.)

B_e = bulk modulus of oil (psi)

V_e = volume with cylinder (in.^{3})

μ = dynamic viscosity of oil
(lb - sec/in.^{2}) .

The value f_o is the 3 db down-point from the area of flat response in the low frequency sensitivity response curve where

$$f_o = \frac{1}{2 \pi T} \quad .$$

In this case T is the time constant of the system and depends on the compliance of the fluid (capacity in the electrical analogy) and the retardation to flow caused by the capillary (resistance in the electrical analogy). The resistance (R) is equal to the pressure drop in the capillary divided by the flow rate. The basis for this is the Hagen-Poiseuille law for laminar flow in

circular pipes.[17]

This derivation is based on the formula for the pressure drop in a horizontal pipe where

$$p_1 - p_2 \text{ or } \Delta p = \frac{32\,\mu\,\ell\,V}{D^2} \quad .$$

The rate of discharge is $Q = \frac{\pi\,D^2\,V}{4}$; combining with the above equation we have

$$\frac{\Delta p}{Q} = \frac{\dfrac{32\,\mu\,\ell\,V}{D^2}}{\dfrac{\pi\,D^2\,V}{4}} = \frac{128\,\mu\,\ell}{\pi\,D^4} \quad .$$

Since $R = \dfrac{\Delta p}{Q}$ then $R = \dfrac{128\,\mu\,\ell}{\pi\,D^4}$.

Compliance (C) of the fluid, the other element of the time constant $(T = RC)$, is the volume of the backing fluid divided by the bulk modulus of the fluid. This evolves from the definition of compliance, i.e., change in volume for a change in pressure

$$C = \frac{\Delta V}{\Delta p} \qquad\qquad\qquad B_e = \frac{\Delta p \cdot V}{\Delta V}$$

then

$$C = \frac{\Delta V}{\Delta p} = \frac{V}{B_e}$$

$$T = RC = \frac{128\,\mu\ell}{\pi\,D^4} \cdot \frac{V}{B_e}$$

$$f_o = \frac{1}{2\,\pi\,T} = \frac{D^4\,B_e}{256\,\mu\,\ell\,V} \quad .$$

---

[17] R. C. Binder, PhD., Fluid Mechanics (Prentice-Hall, Inc., New York, 1955), 2nd ed., p. 119.

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This report presents the salient points of hydrophone
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